A LINEAR PROGRAMMING MODEL FOR USE IN ENGINEER FORCE REQUIREMENTS PLANNING

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THESIS

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ABSTRACT

Current force planning methodology for determining the proper level, mix, and balance of U.S. Army Engineer Forces required to support theater level military operations is examined and a linear programming model is described for use in the planning process. The structure of the linear programming model and feasible ways to derive required parameter values are explained in detail. A test problem and results obtained using the linear programming model are presented to amplify the explanations and to provide a basis for further evaluation and analysis. Alternate model formulation for solving minimum force, minimum cost, or maximum productivity theater force objectives, and extensions for applications of the model in force development and analysis activities are described.

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I. ENGINEER FORCE PLANNING

A. INTRODUCTION

Engineer force planning is a segment of general force planning and analysis activities which include planning for support of current and future military operations and contingencies, and force planning associated with budgeting and force development. Of particular interest is planning conducted for large geographical theaters of operations such as the Pacific and the Mid-East theaters. Such planning requires coordinated effort of planners and specialists representing various branches of the Army who must evaluate and analyze factors such as the mission, the operational situation, enemy characteristics and capabilities, the area of operations, and the logistic support structure and capabilities in order to determine total force requirements and capabilities.

With guidance provided in FM-101-10-1 [1], this evaluation and analysis includes determination of the specific functions and tasks which must be performed, determination of quantitative workload, selection of specific operating units with requisite capability, calculation of the number of operating units required, and provision for command and control structures. In this process, each planner analyzes the mission as a whole and provides input to other planners concerning his support capability and his support

requirements. This paper is primarily concerned with the role of the engineer planner in this integrated process.

B. ENGINEER FORCE PLANNING METHODOLOGIES

Engineer force planning methodologies will be discussed from the point in the planning process that the engineer planner has derived or been given a mix of projects, work, or tasks, which must be constructed, completed, or supported by engineer forces by or for a given time period. Additionally, it will be assumed that general policy constraints for engineer support and general force level constraints have been specified. At this point in the planning process, the engineer planner is faced principally with calculation problems. Current methodology for handling these problems can be grouped into two broad classes, an allocation methodology and a work requirement versus production capability methodology. These methodologies can be used singly or in combination to derive engineer force requirements for large theaters of operation.

The allocation methodology consists of rules for allotting one type of troop unit in fixed proportion to the level, type, and quantity of other troop units. For example, one Engineer Combat Battalion may be alloted for each Infantry, Armored, and Airborne Division, one Engineer Combat Group might be allotted for every four Engineer Combat Battalions and so forth. In this methodology, specific ratios have been derived from historical precedent or have

been set by policy. The method can be used for hasty estimates of requirements or for determination of forces which are not sensitive to workload requirements.

With the second methodology, the engineer planner calculates engineer force requirements by first translating the given project mix to a time-phased construction and support program. He then estimates manhour effort required to complete construction and support for a given time period in this program. From tables of organization and equipment (TOE) and/or other manpower authorization documents, he calculates manhour production capabilities of engineer units suitable for accomplishing the construction and support. Force levels, mix, and balance are then derived by dividing the total manhour effort required by the total manhour production capability per unit.

The results obtained in this manner are sensitive to methods used to estimate requirements and capabilities, and methods for relating production capability, requirements, and numbers by type of engineer units required. In this regard the workload methodology becomes very complex and wide ranges of results can be obtained depending on the manner in which simplifying assumptions are made to reduce the complexity. The model developed in this paper is intended to assist in dealing with this problem area and a fuller understanding of the variables and parameters involved is important to understanding and applying the model.

C. THE WORKLOAD METHODOLOGY

The workload methodology basically involves three steps which include calculation of work requirements in terms of manhours of effort, calculation of engineer troop unit production capability in terms of manhours of capability per unit, and comparing production capability to production requirements to determine the number of troop units required. A flow diagram illustrating this process is attached in Appendix A.

Calculation of work requirements from a given project mix first requires a specific identification of the work involved since the given project mix is usually specified in very general terms. For example, one project may be to construct a 1000 bed hospital. In the strictest sense, the engineer planner must then determine what constitutes a 1000 bed hospital, what type of construction will be used, what materials will be required at what time, a construction schedule, the time-phased type and quantity of manpower and equipment required, and finally the relation of this project to the total construction program. Requirements for a large theater of operations are such that this level of estimation cannot be realistically accomplished in the time allotted for most planning activities unless some prior planning has been done or guidance has been given. To assist planners in this regard, the U.S. Army Corps of Engineers has developed the Engineer Functional Components System.

The Engineer Functional Components System consists of a standard set of theater of operations construction plans, detailed listings of project components by groupings with related total manpower, tonnage and cost requirements, and detailed listings of materiel requirements. This information is published in a set of three manuals, TM 5-301 [2], TM 5-302 [3], and TM 5-303 [4], which provide the planner a means to calculate the bulk of manhour requirements.

From the list of projects the planner first determines the installations required and then the associated facilities. An "installation" is defined to be a balanced grouping of "facilities" designed to be located in the same vicinity. A 1000 bed hospital is typical. A "facility" is a grouping of items and/or sets consisting primarily of construction material in the necessary quantities required to provide a specified service, such as a road bridge, a dispensary, a mile of road, etc. For general planning, a typical installation will consist of some predetermined set of facilities. For specific planning installations can be tailored for a given use by adding or subtracting suitable facilities.

To limit interpretation as to the "type" of construction, the engineer planner is given policy guidance as to the "standard" of construction. In this regard, the Army classifies six "standards" of construction, an example of which is shown in Table 1.1. If not specified otherwise, engineer planners will usually assume projects will be

TABLE 1.1

STANDARDS OF CONSTRUCTION FOR TROOP CAMPS

Standard	DESCRIPTION
1	TOE tents; no engineer materials or effort involved.
2	Class IV tents pitched by using troops; engineer effort for roads and site preparation.
3	Buildings with floors for administration, bathhouses, infirmaries, storehouses, and kitchens. Class IV tents with floors for housing and with earth floors for all other purposes. Roads within the installations are stabilized with local materials. Water piped from central storage tank to infirmaries, bathhouses, and kitchens. Electric distribution to buildings. Pit type latrines.
4	Buildings with floors for all purposes except housing; Class IV tents with floors and wood frames for housing; roads within the installations are stabilized with local materials; water piped from central storage tank to infirmaries, bathhouses, kitchens, and camp exchange; electric distribution to buildings and tent housing. Pit type latrines.
5	Buildings with floors for all purposes. Roads water supply, and latrines are the same as type 4 above; electric distribution to all buildings.
6	Buildings with floors for all purposes; latrines with pipe to carry untreated sewage 1,000 feet beyond the confines of the camp; bituminous surfacing of roads within the installations; water piped from central storage tank to infirmary, bathhouses, latrines, kitchens, and camp exchange; electric distribution to all buildings.

constructed at Standard 2 levels in initial phases of given operations and will be upgraded to higher standards as time, material, and manpower becomes available.

In addition to the major estimates for work required, the planner must consider such factors as climate, weather, management, efficiency, material flow, time phasing of construction tasks, enemy interference and integration of various projects. The Functional Component System helps in a limited way by providing data based on "average" conditions of climate, terrain, state of training, length of time in the theater, negligible enemy interference and other "average" conditions. Unfortunately, what constitutes "average" is not specifically defined. The most specific division made by the system is the distinction between "temperate" and "tropical" climate construction.

Computations are also required in most theater planning to account for repair of damage occasioned during military operations and to account for availability of indigenous resources which can be used to offset new construction requirements. Very little information has been published to assist an engineer planner in these areas. At the present, these computations are strictly judgmental and final solutions obtained can vary widely between planners.

From the "facilities" analyses the planner obtains estimates of the total manhour requirements for all facilities of the project mix. This total is then used in estimating troop unit requirements.

At this point the planner must choose a method for determining the production capability of Engineer troop units. One method available is to use planning guidance from FM 101-10-1 which gives general estimates of "battalion month" production capabilities. In this case, "battalion month" is defined to be the construction effort of an average experienced and properly equipped Engineer Construction Battalion during one month. It is based on full authorized unit strength with each man working a ten-hour day in a six-day week. This method pertains only to Battalions, or Battalions augmented with Light Equipment or Construction Support Companies, and cannot be used for other engineer units.

Production capability would be computed on the basis of the number of men and construction hours available adjusted to account for such factors as efficiency, net production time available, and effects of weather and climate on production effort. As with requirements, production manhours for all skills would be added to obtain a total production capability.

In terms of total manpower, Engineer Battalions usually comprise the bulk of engineer force requirements. Accordingly, current practice is to determine the number of Battalions required and then add on smaller units in consonance with allocation rules or unique work requirements. By dividing total requirements by total production

capability, the planner obtains the number of Battalions to do the construction tasks.

An alternative method is to assume some type of composite unit, such as a Construction Battalion augmented with elements of several types of support units such as Construction Support, Port Construction, Pipeline Construction and/or Railroad Construction Companies, and to compute the production capability of the composite unit. Which supporting units to use would be determined by the type of work required, and the amount apportioned to a Battalion would be determined by allocations specified in tables of organization and equipment.

The number of Battalions determined in this analysis is for one time phase in the total time frame of the military operation. By repeating the work requirements and production capability calculations over successive time periods, the planner develops a set of solutions which depict estimated levels of troop requirements for the entire time span of the operation. These levels are then evaluated to determine one "appropriate" level for the entire operation. Figure 1.1 shows a typical requirement curve which could occur. Current practice is to take the highest figure in the set of solutions obtained and use it as the required troop unit level for the entire operation.

This may not be a final solution since overall constraints may be imposed on total theater force levels. Even though engineer force levels are derived as a function of combat

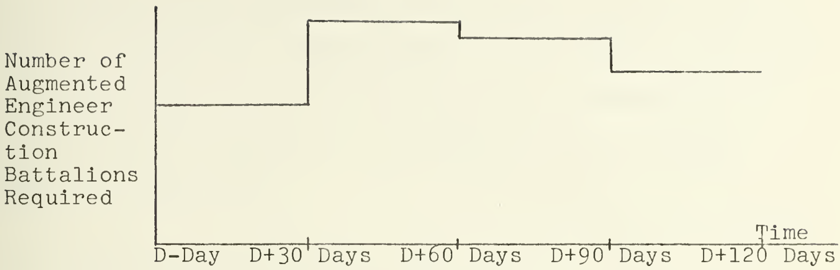


Figure 1.1. Typical Engineer Construction Battalion Force Levels for Various Phases of a Theater Operation

and construction support tasks, which the theater force planners specify as minimum essential for force mission accomplishment, they may be too high or out of balance with the total force structure. In these cases, "balance" means the percentage of engineer forces in each part of the theater force.

Allowable percentages have been derived by historical precedent and may be specified by policy or directive for a given operation. If engineer force levels are out of balance then they must be reduced until proper balance is obtained. In some cases these reductions are made arbitrarily since the computational procedures do not readily permit analyses of requirements tradeoffs or force mix tradeoffs.

In practice, the skilled or experienced planner will recognize overall force constraints and will attempt to influence force levels derived from the workload methodology

by assuming some requirements will be met by use of indigenous resources, by reducing construction manhour estimates, by rephasing or resequencing projects, by increasing troop unit production capabilities estimates, or by varying composite unit mix.

D. POTENTIAL IMPROVEMENTS IN METHODOLOGY

Current methodology can be improved both in regard to allocation and workload methods. The allocation methodology simplifies planner effort by reducing calculation effort but it provides no assurance that work required for a given operation can be accomplished. The typically rigid structure of Engineer troop units provides for very general production. Any specific situation for employment can at best be conceived as a random sample of possible production requirements. Consequently one should assume that the general structure will provide a basis which should be augmented or tailored for specific situations. Extensive tailoring implies that units should be apportioned on the basis of their contribution to satisfying requirements rather than on a basis of their relation to other units.

On the other hand, calculations for the workload methodology are done manually. This does not permit making detailed estimates, critical path analysis, parametric or sensitivity analysis because of time and planner manpower constraints. Requirements estimates, which really drive the solutions, and requirements tradeoffs and force

composition tradeoffs cannot be evaluated in depth since to do so would require considerable recomputation effort.

The workload methodology also does not recognize constraints which may be imposed by specific skills or equipment. Minor improvement could be made if both manhour requirements and production capability were divided into horizontal and vertical groupings. The horizontal grouping would relate to tasks dominated by use of construction equipment whereas the vertical grouping would relate to tasks dominated by manpower such as carpenters, electricians, and so forth. Unfortunately the data base of the Engineer Functional Components System provides no information of this type and planners do not have time to make detailed estimates to obtain it.

It appears that significant improvement in methodology could be made if mathematical programming, critical path analysis, and parametric analysis techniques were introduced. The model to be presented in the next chapter is intended as a start in that direction. It is not intended to replace current methodology but rather to serve as a computational aid which would reduce the manual effort involved in rudimentary calculations and would also permit wider investigation of the variables and parameters involved.

II. MATHEMATICAL DESCRIPTION OF THE MODEL

A. GENERAL

The model is characterized as a static equilibrium, fixed coefficient, linear optimization model. It has a linear objective function which is to be minimized subject to a set of linear production and allocation inequalities, upper bounds, and nonnegativity constraints. Linearity in the model assumes constant returns to scale and basically assumes that production output by construction skill groupings for a mix of engineer troop units can be linearly combined to satisfy production requirements.

It is also assumed that production output by an individual skill grouping is independent of output by other skill groupings and that a given skill requirement can only be satisfied by a similar skill production capability. As an example, carpenter manhour output is independent of crane operator manhour output and crane operator requirements cannot be satisfied by carpenter output.

Finally, it is assumed that production is efficient in the sense that if an optimal solution can be obtained, it will be on the boundary of the feasible production region.

The model consists of five components; an objective function, a set of production constraints, a set of allocation constraints, a set of force level constraints and a set of nonnegativity constraints. The objective of the model is to find the number, by type, of engineer troop units so

as to minimize the total expenditure of engineer effort (manhours), subject to meeting construction requirements for a given time period, with force levels and mix not greater than those specified. Using matrix-vector notation, the model is mathematically described as:

minimize	$z = EX,$	}Objective Function
subject to	$SX \geq W,$	}Production Constraints
	$AX \geq 0,$	}Allocation Constraints
	$IX \leq M,$	}Force Level Constraints
and	$X \geq 0$	}Nonnegativity Constraints

where

z = total manhour production effort, a scalar.

E = an effectiveness coefficient row vector of order n, $(e_1, e_2, \ldots, e_n)$. The element e_j has dimensions of manhours per engineer troop unit j.

X = a column vector of order n, $(x_1, x_2, \ldots, x_n)$. The element x_j represents the unknown number of engineer troop units of type j.

S = an $m \times n$ matrix of engineer unit production capability having elements s_{ij} where

s_{ij} = production of skill grouping i for one engineer troop unit j.

W = a column vector of order m, $(w_1, w_2, \ldots, w_m)$, whose elements represent manhour requirements by skill grouping i to support a given mix of construction projects.

A = a $p \times n$ matrix of allocation constraint coefficients representing specified fixed constraining relationships between elements of the X vector.

I = an $n \times n$ identity matrix.

M = a column vector of order n, $(m_1, m_2, \ldots, m_n)$. The element m_j is a specified upper bound on the total quantity, x_j, of engineer unit type j allowed in the final solution.

i = row indices, 1,2,...,m, representing construction skill groupings.

j = column indices, 1,2,...,n, representing types of engineer units.

The pertinent aspects of the model parameters, variables and their relationships are discussed in the following sections.

B. THE OBJECTIVE FUNCTION

The basic objective in force planning is assumed to be to provide the minimum manpower, or forces, required to meet mission or operational requirements. The objective function of the model is therefore to minimize EX.

The effectiveness coefficient vector, E, represents relative effectiveness of each engineer unit in the X vector. The unknowns, x_j, are expressed in terms of troop units since force planning usually deals with troop units of specified type and size. The model retains the typically rigid structure of such units.

The effectiveness coefficients used in the objective function can be derived in the following manner. Assume that the effectiveness of various engineer units is linear in terms of their contribution to production output. Then a suitable measure of the total effectiveness of all the skills in a unit seems to be the sum of their corresponding

column entries in the production capability matrix S. Mathematically this would be expressed as

$$e_j = \sum_{i=1}^{m} s_{ij},$$

where e_j has units of manhours per troop unit j, and s_{ij} has units of manhours of skill i per troop unit j.

C. THE REQUIREMENTS VECTOR, W

The production requirements vector is a column vector of the form

$$W = \begin{bmatrix} w_1 \\ w_2 \\ \cdot \\ \cdot \\ \cdot \\ w_m \end{bmatrix}$$

where w_i is the total skill i manhour requirements for a given mix of projects. For example, the entries could represent

w_1 = carpenter

w_2 = electrician manhours,

.
.
.

w_m = unskilled labor manhours.

The total number of skill groupings can vary depending on the refinement desired by the planner, or the intentions of sensitivity analysis desired. Skills can be identified

as a general skill area, such as carpenters, or graded skill levels within skill areas such as apprentice carpenter, carpenter helper, master carpenter or carpenter foreman. However, the planner does not have complete freedom in choosing skill groupings since the groupings can be in no greater detail than the corresponding grouping used in making construction estimates.

If the estimates are detailed for some skills and not for others, the planner could consolidate the detailed skill areas. If such consolidations are made he should be careful to preserve the independence of skill areas.

A derivation of the requirements vector will be presented below. To illustrate the process, suppose that the matrix of Table 2.1 has been developed from the Engineer Functional Components System, and that from construction estimates for the facility construction the matrix of manhour requirements for the facilities of Table 2.1 has been developed and corresponds to Table 2.2.

From the project list and data from tables such as 2.1 and 2.2 form; (1) a $p \times q$ matrix F relating installation-facility requirements whose entries, f_{ij}, represent the quantity of facility i required for one unit of installation j; (2) an $m \times t$ matrix R relating facility-manhour requirements whose entries, r_{ij}, represent the manhours of skill i required for one unit of facility j; (3) a column vector P, of order q, whose entries, p_j, would be the quantity of each installation type j required for construction within a given

TABLE 2.1

INSTALLATION - FACILITY REQUIREMENTS

Facility	Installation			
	Troop Camp 3000 Man	Hospital 1000 Bed	Ammo Storage	Admin Space
Frame, Roof, Foundation	1.0	1.0	0	1.0
Cladding, 8' x 100'	74.2	47.0	74.0	9.4
Floor Concrete 2", 1000 SF	160.0	110.0	2.4	10.0
Kitchen Bldg.	15.0	3.0	0	0
Latrine, Pit Type, 8 Seats	18.0	6.0	2.0	2.0
Storehouse 20' x 100'	3.0	0	0	0

TABLE 2.2

FACILITY - MANHOUR REQUIREMENTS

Construction Skill	Facility					
	Frame Roof Foundation	Cladding 8' x 100'	Floor Conc 2" 1000 SF	Kitchen Bldg	Latrine Pit Type 8 Seats	Storehouse 20' x 100'
Carpentry	6,000	100	2	70	16	16
Electrical	0	0	0	10	1	4
Plumbing	0	0	0	10	0	0
Masonry	0	0	12	0	0	2
Common Labor	8,800	10	30	0	0	10

or estimated time period; (4) a column vector Q, of order t, whose entries, q_k, would be the quantity of the k^{th} type of facility required for construction within a given or estimated time period; (5) a column vector D, of order t, whose entries, d_k, would be "corrections" to installation facility requirements (i.e., additions or deletions) plus possible separate facility requirements such as bridges, dispensaries, roads, etc., for a given or estimated time period; and (6) a scalar adjustment factor, λ, to adjust manhour requirements calculations to account for deviations from efficiency, climate, weather, management, and enemy interference factors assumed in data base construction estimates.

The vector of the number by type of facilities required to support installation requirements is obtained from the matrix product N = FP. The vector sum

$$Q = \begin{bmatrix} N \\ 0 \end{bmatrix} + D,$$

then gives total facilities requirements. The null vector, 0, must be included since the vector D would have the same dimension as the vector N only if there were no provision for separate facilities in the facility - manhour matrix. Finally, the production requirements vector W can be obtained from

$$W = \lambda RQ.$$

D. PRODUCTION CONSTRAINTS

Production constraints consist of the requirements vector W, the production capability matrix S, and relationships between requirements and capability. For example, the S matrix corresponding to the data of Tables 2.1 and 2.2 might look like Table 2.3.

TABLE 2.3

MANHOUR CAPABILITIES PER ENGINEER TROOP UNIT

Construction Skill	Engineer Unit			
	Type 1	Type 2	Type 3	Type 4
Carpentry	22,500	27,000	14,000	20,000
Electrical	5,700	8,000	3,000	5,000
Plumbing	5,700	8,000	2,000	5,000
Masonry	1,800	8,000	900	2,000
Common Labor	10,000	20,000	2,000	25,000

The S matrix can be derived from basic data in the following manner. Let U be an m x n matrix where each entry u_{ij} represents the number of men with skill i in unit j. Let h be a scalar representing the effective proportion of construction hours available during the given construction period; that is,

$$h = \text{(number of days)(hours/day)(production factor)}.$$

The number of construction days available and the

construction hours per day are obtained from the operational situation. The production factor would be a parameter accounting for efficiency, management, climate, weather, or, in general, that portion of total time which would be available for effective production. Time considered not available would be that consumed in other than primary production duties such as security, kitchen police, messing, rest and recuperation, personnel needs, and unit movement. The production capability matrix S for the model can be determined from the product

$$S = hU.$$

With the manhour requirements and production capability coefficients specified, the associated constraint set can be written as $SX \geq W$ or $SX = W$.

In force planning, the workload is generated by estimating only minimum operational requirements. The planner must also provide for sufficient resources to upgrade facilities to higher standards once all minimum standard construction requirements have been met and to allow for uncertainties in project requirements. If the constraint were equality, no surplus resources would be available for these additional requirements. Thus, it appears more reasonable to consider the inequality relationship.

E. FORCE LEVEL AND ALLOCATION CONSTRAINTS

In present force planning methodology, force level and allocation constraints are not seriously considered until

an initial solution has been developed by all planners. Once levels have been obtained for all forces, the engineer forces are then compared with the level, mix, and balance of theater forces and adjustments are made as directed or necessary to bring the entire force into balance. Thus, at some point in the planning process, the planner is faced with the problem of force level and/or allocation constraints. The model structure incorporates these constraints from the beginning. Consequently, when the model is solved, either a balanced solution results or infeasibility is detected.

Force level constraints are generally of the form

$$x_j \leq m_j,$$

where x_j is the solution quantity of some type of engineer troop unit and m_j is the associated maximum quantity allowed. These constraints arise where, for example, the national inventory of Construction Battalions may be such that only a certain number can be made available for use in a specified theater. These constraints, when combined into one set, can be expressed in matrix notation as

$$IX \leq M.$$

Allocation constraints, in contrast to the force level constraints, are usually established by policy or precedence and take the form:

$$\frac{x_2}{x_1} \leq \frac{a}{b},$$

where a and b are positive constraints. This form can be rewritten as the linear inequality

$$ax_1 - bx_2 \geq 0.$$

For example, x_1 may be the number of Construction Battalions and x_2 the number of Construction Support Companies which could be allotted in the ratio of one Support Company per three Construction Battalions.

All allocation constraints can be collected into a set described by

$$AX \geq 0,$$

where A matrix consists of the appropriate allocation relationships.

In the absence of policy guidance, force level constraints can be obtained from comparative situations or could be developed using guidelines as to historic ratio of engineer forces to theater forces such as published in Army manual FM 101-10-1 [1]. Allocation relationships are published in Army tables of organization and equipment.

III. MODEL TEST AND ANALYSIS

A. TEST PROBLEM

1. Problem Formulation

The test problem was to find an appropriate level, mix, and balance of general construction support units to satisfy a given mix of general construction requirements for a 120 day operations period.

The example problem was formulated to address only the general construction support case although, in the most general engineer force planning case, certain projects of the required project list can be only accomplished by certain well defined units. For example, map and topographic support can only be provided by map and topographic units. Direct combat support is provided by units trained and structured to provide such support. However, other projects such as general construction support, can be provided by a variety of units and tradeoffs between units must be made. The model can accommodate all of these aspects.

The formulation was typical in scope for theater level general construction support requirements and was patterned from a similar problem being used by the Department of the Army to test and evaluate another large scale logistic computer model. While this problem constitutes a typical mix of projects, the mix has been randomly generated and solutions obtained cannot be used to critically analyze current troop unit structures.

No one solution is offered since any solution to engineer force levels must be viewed in context with total theater force levels. Since the problem addressed only engineer requirements, and only the general construction case, the solutions can best be described as initial. Furthermore, no attempt was made to justify any one solution since the intent of the test was to analyze the model and to determine various ways in which it would be used to assist or improve current force planning methodology.

2. Construction Requirements

Minimum essential installation and separate facility construction requirements to support the 120 day operation were assumed to be those given in Tables 3.1, 3.2, 3.3, and 3.4. In developing these tables, preference was given to wood frame structures for installations or facilities which could be constructed of either wood or steel.

3. Available Troop Units

Types of engineer troop units available for general construction support were assumed to be Engineer Combat Battalions, Engineer Construction Battalions, Engineer Light Equipment Companies, Engineer Construction Support Companies, Engineer Port Construction Companies, Engineer Dump Truck Companies, Engineer Pipeline Construction Support Companies, and cellular units such as Welding Teams, Diving Teams, Electrical Power Teams, and other similar teams as required.

TABLE 3.1

INSTALLATION AND SEPARATE FACILITY
REQUIREMENTS FOR D-DAY TO D+30

Item	TM 5-301 Code No.	Quantity
a. Installations		
Administration 25,000 SF	A2.132	10
Hospital, 200 Bed	G4.122	8
Hospital, 500 Bed	G6.122	4
Hospital, 750 Bed	G7.122	2
Hospital, 1000 Bed	G8.122	2
Military Prisoner Stockade, 250 Man	ND1.120	4
P.O.W. Camp, 2000 Man	NP5.120	1
Troop Camp, 250 Man	NT1.132	2
Troop Camp, 500 Man	NT2.132	2
Troop Camp, 1500 Man	NT4.132	10
Troop Camp, 3000 Man	NT5.132	3
Tank Farm, POL, 250,000 BBL	QBT5.046	3
Pipeline, POL, 6" x 17 mi	QD2.036	2
Drum and Can Loading, POL	QE1.036	2
b. Separate Facilities		
Hospital Facility, Lab and Dental	513422	10
Hospital Facility, Dispensary, 30' x 90'	512322	10
Hospital Facility, Dispensary, 30' x 70'	512421	10
Shop, Automotive, Arm. Rebuild	214321	2
Shop, Ordnance Field Maint.	214221	1
Shop, Ordnance, G.P. Rebuild	218221	1
Shop, Ordnance Park Company	218121	1
Railroad Bridge, 50' Span	861622	10
Railroad Bridge, 40' Span	861618	20
Railroad Bridge, 30' Span	861610	20
Railroad Bridge, Substructure, 50' Span	861706	10
Railroad Bridge, Substructure, 60' Span	861709	10
Railroad Bridge, Substructure, 45' Span	861705	80
Track Single, RR, 1 Mile	861001	17.5
Turnout, RR, No. 8	861301	10
Road Bridge, 110'-119' Span	852123	8
Road Bridge, 80'-85' Span	852117	2
Road Bridge, 60'-67' Span	852113	1
Road Bridge, Substructure, Max 180'Span	861065	6
Road Bridge, Substructure, 80' Span	852203	4
Road Bridge, Substructure, 60' Span	852202	2
Road Bridge, Decking, 26' x 50'	852188	20.4

TABLE 3.1 (Continued)

Item	TM 5-301 Code No.	Quantity
Road Bridge, Substructure, Max 128' Span	852404	4
Road, 2 Lanes, 3" Hot Mix, Asphalt	852908	30
Landing Ramp for LST and DUKS, 15' x 100' x 12"	152001	10
Landing Ramp for LST and DUKS, 25' x 100' x 12"	152002	10
Hot Mix Asphalt Production, 1000 CY	853002	50
Surfacing, Dist Palliative, 1000 SY	111111	50
Landing Ramp for Landing Craft, 1000 SY	152003	10
Road, 1 Lane, 4", Earth or Crushed Stone, 1 mi	851202	20
Aggregate Production, 100 CY	853005	400

TABLE 3.2

INSTALLATION AND SEPARATE FACILITY REQUIREMENTS FOR D+30 TO D+60

Item	TM 5-301 Code No.	Quantity
a. Installations		
Administration, 50,000 SF	A3.132	1
Storage, Ammunition, 5,000 Ton	DA1.120	10
Storage, Ammunition, 15,000 Ton ADSEC	DA2.132	2
Storage, Ammunition, 15,000 Ton BASEC	DA2.152	2
Storage, Dry Cargo, 25,000 SF, Covered	DSC2.132	4
Storage, Dry Cargo, 50,000 SF, Covered	DSC3.132	2
Storage, Dry Cargo, 50,000 SF, Open	DSO1.020	7
Storage, Dry Cargo, 100,000 SF, Open	DSO2.020	4
Storage, Dry Cargo, 200,000 SF, Open	DSO3.020	2
Port, 15' Tide, 1440 Tons/Day	FP3-1.152	1
Port, 25' Tide, 1440 Tons/Day	FP5-1.152	1
Hospital, 750 Bed	G7.122	4
Military Prisoner Stockade, 250 Man	ND1.120	1
P.O.W. Camp, 500 Man	NP2.120	2
P.O.W. Camp, 1000 Man	NP3.120	2
Troop Camp, 500 Man	NT2.132	2
Troop Camp, 3000 Man	NT5.132	2
Tank Farm, POL, 100,000 BBL	QBT2.036	4
Pipeline, POL, 6" x 17 Miles	QD2.036	1.5

TABLE 3.2 (Continued)

Item	TM 5-301 Code No.	Quantity
b. Separate Facilities		
Ice Plant, 15 Ton	432321	6
Warehouse, Refrigerated, 40' x 60'	431525	4
Warehouse, Refrigerated, 80' x 220'	431622	2
Warehouse, Refrigerated, 32' x 40'	431522	9
Hospital Facility, Lab and Dental	513422	3
Hospital Facility, Dispensary, 30' x 90'	512322	3
Hospital Facility, Dispensary, 30' x 70'	512421	3
Shop, Ordnance, G.P. Rebuild, 120' x 240'	218211	3
Shop, Ordnance, Motor Veh.Assy., 120' x 200'	224111	2
Pier, Wharf, Rehabilitation, Scheme I	152501	2
Pier, Wharf, Rehabilitation, Scheme II	150201	2
Pier, Wharf, Rehabilitation, Scheme III	150301	2
Pier, Wharf, Rehabilitation, Scheme IV	150401	2
Pier, Wharf, Rehabilitation, Scheme V	150501	2
Jetty, Pol, 1000', w/20' x 40' wharf	153101	2
Wharf, Rehabilitation, 75' x 500'	152401	2
Tanker Mooring, POL, 7 Leg, 60' Depth	122110	4
Pipeline, Submarine, POL, 60' Depth	122317	4
Railroad Bridge, 123' Span	861952	1
Railroad Bridge, Type F Pier	861729	2
Railroad Bridge, 100' Span	861644	1
Railroad Bridge, Substructure, Type F Pier	861728	2
Track Single, Railroad, 1 Mile	861001	6
Turnout, Railroad, No. 8	861301	5
Road Bridge, 80'-85' Span	852117	3
Road Bridge, 60'-67' Span	852113	5
Road Bridge, Substructure, 80' Span	852203	6
Road Bridge, Substructure, 60' Span	852202	10
Road Bridge, Decking, 26' x 50'	852188	10.8
Road, 2 Lane, 3" Hot Mix, Asphalt	852908	20
Landing Ramp for LST and DUKS, 25' x 100' x 12"	152002	4

TABLE 3.3

INSTALLATION AND SEPARATE FACILITY REQUIREMENTS FOR D+60 TO D+90

Item	TM 5-301 Code No.	Quantity
a. Installations		
Administration, 10,000 SF	A1.132	3
Storage, Ammunition, 5,000 Ton	DA1.120	7
Storage, Ammunition, 15,000 Ton, ADSEC	DA2.132	1
Storage, Ammunition, 15,000 Ton, BASEC	DA2.152	1
Storage, Dry Cargo, 12,000 SF, Covered	DSC1.132	5
Storage, Dry Cargo, 50,000 SF, Covered	DSC3.132	2
Storage, Dry Cargo, 50,000 SF, Open	DS01.020	5
Port, 15' Tide, 1440 Tons/Day	FP3-1.152	1
Port, 25' Tide, 1440 Tons/Day	FP5-1.152	1
Hospital, 200 Bed	G4.122	6
Hospital, 300 Bed	G5.122	8
Hospital, 500 Bed	G6.122	4
P.O.W. Camp, 250 Man	NP1.120	3
P.O.W. Camp, 500 Man	NP2.120	2
Troop Camp, 250 Man	NT1.132	2
Troop Camp, 1000 Man	NT3.132	1
Tank Farm, POL, 50,000 BBL	QB1.036	4
Pipeline, POL, 6" x 17 Miles	QD2.036	0.5
b. Separate Facilities		
Ice Plant, 15 Ton	432321	5
Warehouse, Refrigerated, 40' x 60'	431525	3
Warehouse, Refrigerated, 80' x 220'	431622	1
Hospital Facility, Dispensary, 30' x 90'	512322	3
Shop, Ordnance, Field Maintenance	214221	1
Pier, Wharf, Rehabilitation, Scheme IV	150401	1
Wharf, Timber, 60' x 500', 15' Tide	152102	1
Pier, RR Approach Trestle, 25' Tide	150606	2
Wharf, Rehabilitation, 35' x 500'	152401	1
Wharf, Timber, 60' x 500', 25' Tide	152103	1
Tanker Mooring, POL, 7 Leg, 60' Depth	122110	4
Railroad Bridge, 50' Span	861622	4
Railroad Bridge, 40' Span	861618	6
Railroad Bridge, Substructure, 50' Span	861706	8
Railroad Bridge, Substructure, Max 45' Span	861705	6
Track Single, Railroad, 1 Mile	861001	3
Turnout, Railroad, No. 8	861301	1
Road Bridge, 110'-119' Span	852123	3
Road Bridge, Substructure, Max 180' Span	861065	2
Road Bridge, Decking, 26' x 50'	852188	6
Road Bridge, Substructure, 110'-128' Span	852404	2
Road, 2 Lanes, 3" Hot Mix, Asphalt	852908	10
Landing Ramp for LST and DUKS, 15' x 100' x 12"	152001	4

TABLE 3.4

INSTALLATION AND SEPARATE FACILITY
REQUIREMENTS FOR D+90 TO D+120

Item	TM 5-301 Code No.	Quantity
a. Installations		
Storage, Ammunition, 5,000 Ton	DA1.120	3
Storage, Ammunition, 15,000 Ton, ADSEC	DA2.132	2
Storage, Ammunition, 15,000 Ton, BASEC	DA2.152	2
Storage, Dry Cargo, 12,000 SF, Covered	DSC1.132	12
Storage, Dry Cargo, 50,000 SF, Open	DS01.020	5
Hospital, 100 Bed	G3.122	10
Hospital, 300 Bed	G5.122	6
Hospital, 750 Bed	G7.122	2
Hospital, 1000 Bed	G8.122	2
P.O.W. Camp, 500 Man	NP2.120	2
P.O.W. Camp, 2000 Man	NP5.120	1
Troop Camp, 250 Man	NT1.132	2
Troop Camp, 1000 Man	NT3.132	1
Tank Farm, POL, 50,000 BBL	QB1.036	1
b. Separate Facilities		
Warehouse, Refrigerated, 40' x 60'	431525	3
Warehouse, Refrigerated, 80' x 220'	431622	1
Warehouse, Refrigerated, 32' x 40'	431522	4
Hospital Facility, Dispensary, 30' x 70'	512421	3
Shop, Ordnance, Motor Vehicle Assembly	224111	1

4. Construction Policy

The following construction policy was assumed for construction standards and priorities. All construction requirements were to be completed to minimum standards (Standard 2). As construction effort became available after minimum-standard requirements were met, upgrading of existing facilities to Standard 3 or higher was to be initiated with surplus construction support available.

For priorities, it was assumed that repair of existing lines of communications facilities had priority over other construction requirements. Construction of new ports and lines of communications facilities had priority over medical and logistic facility requirements. Medical and logistic facility requirements had construction priority over administrative and personnel housing requirements, troop housing, administrative space, staging areas, and replacement centers. Percentages of construction which were allowed to be accomplished in each of the four 30 day increments of the operation are shown in Table 3.5.

5. Construction Parameters

Construction parameters in the problem included an adjustment factor to relate conditions assumed in manhour construction estimates to conditions assumed in the test problem, the number of days available for construction, the daily work time available and a factor for effective production time for troop units. It was assumed that the military operation was conducted in a temperate climate and that the

TABLE 3.5

PRIORITIES AND ALLOWABLE PERCENTAGES OF CONSTRUCTION

Item	Priority	Allowable Percentages			
		D-Day to D+30	D+30 to D+60	D+60 to D+90	D+90 to D+120
Repair of Existing Lines or Communication (LOC), New Ports, Landing Facilities	1	100	100	100	100
Repair of Ports, Piers, Wharfs	2	100	100	100	100
Construction of New Roads, Railroads and Upgrading of Existing LOC	3	100	100	100	100
Medical Facilities	4	100	100	100	100
Logistic POL Facilities	5	100	100	100	100
Storage Facilities (Open)	6	75	100	100	100
Storage Facilities (Covered)	7	75	100	100	100
Ammunition Storage Facilities	8	50	75	100	100
Administrative Facilities	9	0	50	75	100
Troop Camps, Staging Areas, Replacement Centers	10	0	50	75	100
P.O.W. Camps	11	100	100	100	100

construction was accomplished under conditions equivalent to those assumed in deriving construction estimates. Thus the requirements manhour adjustment factor was assumed to be 1.0. The work schedule for each 30 day increment was assumed to be 30 days at 8 hours per day per man. The production factor for troop units was assumed to be 0.8. This factor was derived basically from Army manpower authorization criteria adjusted to account for unit efficiency and assumed average working conditions.

6. Bounds and Allocation Constraints

Problem solutions were obtained under assumptions of (1) no bounds or allocation constraints; (2) bounds but no allocation constraints; and (3) both bounds and allocation constraints. Bounds were used as variable parameters in the problem, and solutions were obtained by iterating or changing their values. A typical set of bounds and allocation constraints used to obtain initial solutions are shown in Table 3.6. These values for bounds were chosen arbitrarily, whereas allocation ratios were obtained from appropriate tables of organization and equipment.

7. Construction Estimates and Skill Groupings

Construction estimates used to formulate data for the problem were drawn from labor and equipment estimate summaries provided by the Office Chief of Engineers. These summaries were originally used to develop manhour information published in the Engineer Functional Components System. The summaries were not current but were deemed suitable for

TABLE 3.6

BOUNDS AND ALLOCATION CONSTRAINTS USED
TO OBTAIN INITIAL SOLUTIONS

Engineer Troop Unit	Constraint: Upper Bound	Constraint: Allocation One Per
Combat Battalion	30	
Construction Battalion	30	
Light Equipment Company	8	4 Combat Battalions
Construction Support Co.	10	3 Construction Battalions
Dump Truck Company	15	4 Combat Btns., and/or 3 Constr. Btns.
Port Construction Co.	8 8	4 Construction Battalions
Pipeline Constr. Spt. Co.	10	Combat Btn. and/or Constr. Btn.

testing the model. In most cases, skill groupings used in the summaries were quite general and did not exactly match current troop unit structure. The differences found were mainly in skills which have been changed due to changes in construction equipment and in gradation of skill levels within skill groupings. To offset this difference, the set of skill groupings used in the problem were mainly those obtained from the summaries. The skill groupings used are shown in Table 3.7.

TABLE 3.7

SKILL GROUPINGS FOR FACILITY AND TROOP UNIT MANHOUR MATRICES

Skill Grouping: Horizontal	Skill Grouping: Vertical
Construction Foreman	Construction Foreman
Surveyor	Carpenter
Survey Recorder	Carpenter Helper
Rodman-Tapeman	Structures Specialist
Quarry Supervisor	Electrician and Power Lineman
Quarry Machine Operator	Electrician Helper
Powderman	Plumber
Asphalt Finisher Operator	Plumber Helper
Asphalt Production Specialist	Mason
Asphalt Distributor Operator	Heating and Ventilation Specialist
Concrete Production Specialist	Sheet Metal Worker
Asphalt Equipment Helper	Refrigeration Specialist
Crane-Shovel Operator	Painter
Crane Operator	Master Diver
Grader Operator	Diver Helper
Crawler Tractor Operator	Rigger
Wheel Tractor Operator	Combat Construction Specialist
Loader Operator	Construction Helper (Pioneer)
Air Compressor Operator	
Cement Mixer Operator	
Ditching Machine Operator	
Power Roller Operator	
Water Distributer Operator	
Hoist Operator	
Pile Driver Operator	
Pipeline Specialist	
Pipeline Helper	
Heavy Dump Truck Driver	
Light to Medium Truck Driver	
Heavy Truck Driver	
Engineer Equipment Repairman	
Draftsman	
Pipeline Truck Driver	
Welder	

B. SOLUTION METHODOLOGY

The mathematical model described in Chapter II was formulated and used to solve the problem. Fixed parameters were used to establish data which could be operated on by control variables to determine engineer forces required to satisfy requirements within specified constraints for each of the four 30 day phases in the problem.

Fixed parameters included: (1) the number and type of facilities required by each installation; (2) manhour requirements by skill groupings for each facility; and (3) manpower by skill groupings for standard Engineer Troop Units. These data were obtained from the Engineer Functional Components System [2], labor and equipment summaries, and tables of organization and equipment.

Control variables included: (1) quantities of installation and separate facilities required for each phase of the operation; (2) construction priorities and percentage allowable construction; (3) a requirements manhour adjustment factor; (4) construction work schedule parameters including the number of days, hours per day, and a production factor; (5) types of Engineer Troop Units available; (6) skill groupings; (7) bounds; and (8) allocation factors.

A computer model was devised to handle the entire problem on the Naval Postgraduate School's IBM 360/67 computer system. The computer model consisted of three submodels. The first submodel was used to establish the required data and to calculate the requirements vector, W,

and the production capability matrix, S, for each of the four phases of the problem. These results were then input to a second computer submodel in which control parameters were specified for final formulation of the mathematical model. This model calculated effectiveness coefficients, final production matrix entries, final requirements, and established bound and allocation constraints. This program was also equipped with a capability to create dummy troop units with skill mix derived as ratios proportionate to construction requirement ratios. At this point the mathematical model was completely specified and ready for solution using the IBM Mathematical Programming System /360 Linear Programming model [19].

The solutions to the linear programming (L.P.) problem were then evaluated. If the problem was shown to be infeasible then the cause of the infeasibility was examined, suitable changes were made in control variables to attempt to remove the infeasibility, and the L.P. problem was then resolved. This was repeated until an optimal solution was obtained. A flow chart showing the computational procedure used is included in Appendix B.

As a matter of interest, each of the first two computer programs required less than 130,000 bytes of computer memory and 15 seconds of time. Memory requirements, for the linear programming solutions were less than 100,000 bytes and time requirements averaged less than six seconds to obtain solutions for each phase of the problem.

C. SOLUTIONS

For better correlation of Engineer Combat Battalion skills with skills of other construction units, the Battalion skills were apportioned as shown in Table 3.8.

Some control variables were kept constant for all of the solutions presented below. These are shown in Tables 3.9 and 3.10.

Seven types of standard engineer units were considered available for all four phases of the problem. That portion of the production capability matrix representing these units thus remained constant for all four phases and is shown in Table 3.11. Effectiveness coefficients used for the objective function were the total manhour values shown in the table.

Requirements vectors varied for each phase due to changes in project mix and changes in percentage allowable construction. Percentage construction not allowed during a phase was carried over to the next phase and added to new construction requirements for that phase. Construction requirements for each phase are shown in Table 3.12.

Initial solutions were attempted using only the seven standard Engineer Units, with bounds and allocations as shown in Table 3.6. No feasible solution could be found. A solution was found, however, when bound and allocation constraints were completely removed. It was not considered to be acceptable since the levels of forces were exceptionally high with large surplus in most skill areas.

TABLE 3.8

APPORTIONMENT OF SELECT ENGINEER COMBAT BATTALION SKILLS TO CONSTRUCTION SKILL GROUPINGS

Engineer Combat Battalion		Apportionment Skill	
Skill	Quantity	Grouping	Quantity
Demolition Specialist	72	Powderman	2
Cement Mixer Oper.	1	Pipeline Constr.Spec.	9
Carpenter	5	Carpenter	47
Carpenter Helper	1	Structures Specialist	39
Electrician	5	Electrician	23
Electrician Helper	1	Plumber	22
Plumber	4	Mason	54
Plumber Helper	1	Heat and Vent Specialist	11
Mason	1	Construction Helper	119
Heat and Vent Specialist	1	Total	326
Sheet Metal Worker	1		
Painter	1		
Combat Constr. Spec.	160		
Pioneer	72		
Total	326		

TABLE 3.9

CONTROL VARIABLES KEPT CONSTANT FOR ALL SOLUTIONS

Variable	Value
Manhour Requirements Adjustment Factor	1.0
Number of Days	30
Number of Hours Per Day	8
Troop Unit Production Factor	0.8

TABLE 3.10

SKILL GROUPING CONSOLIDATIONS KEPT CONSTANT FOR ALL SOLUTIONS

Data Base Skill Groupings	Consolidated Grouping for Problem Solution
Surveyor Recorder; Rodman-Tapeman	Rodman-Tapeman
Quarry Supervisor; Quarry Machine Operator	Quarry Operations
Asphalt Finisher Operator; Asphalt Production Specialist; Asphalt Distributor Operator; Asphalt Helper	Asphalt Operations
Crane-Shovel Operation; Crane Operator	Crane Operator
Crawler Tractor Operator; Wheel Tractor Operator	Tractor Operator
Cement Mixer Operator; Painter; Construction Helper	Construction Helper
Pipeline Specialist; Pipeline Helper	Pipeline Specialist
Light-Medium Truck Driver; Pipeline Truck Driver	Light-Medium Truck Driver
Carpenter; Carpenter Helper	Carpenter
Electrician; Electrician Helper	Electrician
Plumber; Plumber Helper	Plumber
Heating and Ventilation Specialist; Sheet Metal Worker	Heating and Ventilation Specialist
Master Diver; Diver Helper	Diver

TABLE 3.11

PRODUCTION CAPABILITY FOR STANDARD ENGINEER UNITS (1000 MANHOURS)

Skill	Engineer Unit						
	Combat Bn.	Constr. Bn.	Light Eq.Co.	Constr. Spt.Co.	Dump Trk.Co.	Port Constr.Co.	Pipeline Constr.Co.
Foreman (Horiz.)	4.800	6.528	2.304	0.768	1.536	0	2.880
Surveyor	0.192	0.384	0	0	0	0.192	0
Rodman-Tapeman	0.192	1.152	0	0	0	0.576	0
Quarry Opns.	0	1.728	1.728	3.264	0	0	0
Powderman	0.384	0.384	0.768	1.152	0	0	0
Asphalt Opns.	0	1.344	0.768	4.032	0	0	0
Concrete Production	0	1.152	0.192	0	0	0.384	0
Crane Operator	1.152	2.880	2.304	1.920	0	1.920	0.960
Grader Operator	1.536	3.456	3.456	0	0	0	0
Tractor Operator	3.840	13.440	4.992	1.536	0	1.152	0.384
Loader Operator	4.992	3.264	1.536	0	0	0.384	0.384
Air Comp. Op.	0.960	2.880	0.768	1.152	0	1.344	0.192
Ditch Mach. Op.	0	0.384	0.576	0.384	0	0	0
Power Roll Op.	0	1.344	0.192	0.576	0	0	0
Water Dist. Op.	0	1.152	0.576	0	0	0	0
Hoist Op.	0	0	0	0	0	0.768	0
Pile Dr. Operator	0	0	0	0	0	0.768	0
Pipeline Spec.	1.728	0.192	0	0	0	1.152	10.368
Hvy. Dump Trk. Op.	10.368	8.832	0	2.496	10.752	0	0
Lt-Med. Trk. Driver	0.384	0.384	0	0	0	1.344	2.304
Hvy. Veh. Driver	0	6.336	3.840	0.576	0	3.264	0
Engr. Equip. Rpmn.	5.184	13.056	4.800	4.224	0	2.496	0.960
Draftsman	0.192	1.344	0	0	0	0.768	0
Welder	0.192	2.112	0.384	0.384	0.192	2.112	3.840

TABLE 3.11 (Continued)

Skill	Engineer Unit						
	Combat Bn.	Constr. Bn.	Light Eq.Co.	Constr. Spt.Co.	Dump Trk.Co.	Port Constr.Co.	Pipeline Constr.Co.
Foreman (Vert)	4.992	5.184	0	0	0	1.728	0
Carpenter	9.024	17.280	0	0	0	2.688	1.728
Structures Sp.	7.488	1.152	0	0	0	1.152	1.728
Electrician	4.416	7.104	0	0	0	0.768	0
Plumber	4.244	7.104	0	0	0	0.384	0
Mason	10.368	2.304	0	0	0	0.384	0
Heat. and Vent. Sp.	2.112	0.384	0	0	0	0	0
Refrig. Spec.	0	0.576	0	0	0	0	0
Diver	0	0	0	0	0	2.688	0
Rigger	0	0	0	0	0	1.536	1.728
Constr. Helper	22.848	3.840	0	0	0	2.688	0
Total Horizontal	47.520	75.648	29.184	22.464	12.480	19.968	22.272
Total Vertical	54.048	43.008	0	0	0	12.672	5.184
Total Manhours	101.568	118.656	29.184	22.464	12.480	32.640	27.456

TABLE 3.12

CONSTRUCTION REQUIREMENTS (1000 MANHOURS)

Skill	D-Day to D+30	D+30 to D+60	D+60 to D+90	D+90 to D+120
Foreman (Horiz)	45.969	72.715	72.048	68.338
Surveyor	8.527	35.167	30.147	28.654
Rodman-Tapeman	17.993	68.951	52.489	49.294
Quarry Opns.	26.016	12.192	6.787	10.502
Powderman	2.409	1.108	0.628	0.972
Asphalt Opns.	24.061	11.694	5.766	1.760
Concrete Production	0	0.228	0	0
Crane Op.	28.193	65.602	49.667	10.952
Grader Op.	20.950	60.332	47.365	52.096
Tractor Op.	89.299	241.753	185.154	194.431
Loader Op.	0.456	0.157	0.068	0.037
Air Comp. Op.	4.231	18.554	11.865	0.980
Ditch Mach. Op.	2.426	1.506	3.318	3.069
Power Roll. Op.	3.551	11.734	8.532	10.475
Water Dist. Op.	3.628	5.318	2.703	4.879
Hoist Op.	0.060	0.952	0	0
Pile Dr. Op.	2.320	16.332	13.468	0
Pipeline Sp.	211.559	95.777	93.038	62.297
Hvy.Dump Trk. Op.	49.234	119.658	92.591	82.426
Light-Med Trk. Dr.	39.907	52.058	46.435	42.394
Hvy. Veh. Dr.	14.682	21.418	25.685	22.355
Engr. Equip. Rpmn.	7.764	54.206	56.384	53.635
Draftsman	2.274	8.249	6.070	6.150
Welder	1.662	49.609	1.786	0.186
Foreman (Vert)	58.203	91.238	106.434	89.078
Carpenter	411.432	925.032	1003.759	679.243
Structures Sp.	14.924	17.180	10.072	5.184
Electrician	136.283	109.144	176.452	150.410
Plumber	193.477	94.024	196.850	198.936
Mason	4.570	30.287	31.537	27.301
Heat. and Vent.Sp.	5.522	9.892	10.752	7.439
Refrig. Sp.	0	7.120	2.480	3.760
Diver	0	12.364	1.680	0
Rigger	2.160	41.134	8.454	2.523
Constr. Helper	673.543	1234.903	1087.553	1064.555
Total Horizontal	943.942	1642.719	1355.771	1238.159
Total Vertical	1163.342	1954.865	2092.247	1696.151
Total Manhours	2107.284	3597.584	3448.018	2934.310

The "unconstrained" results obtained were explainable by shortfalls (i.e., manpower shortages in requisite skills) in standard unit structure for a subset of the total set of skills. This exercise showed the value of the model's capability to detect infeasibility and to indicate which skills would have to be changed to tailor the units for the given construction situation.

By analyzing the infeasibilities detected it was possible to create dummy cellular troop units for a specific skill or subset of skills and add such units to the production set. Similar units were formed for skills which did not have infeasibilities but which had little or no slack at the time infeasibility was detected.

The dummy cellular units which were formulated are shown in Table 3.13. These units were either drawn from appropriate tables of organization and equipment or were arbitrarily sized as typical squad or company troop units.

With this augmentation a feasible optimal solution was obtained; Table 3.14 shows troop levels and Table 3.16 shows surplus construction capability. Comparisons of total manhours required versus total effective manhours available at optimality are shown in Table 3.15.

An alternative approach taken to resolve the infeasibility problem was to formulate dummy units representing Battalion size forces. Three types of units formulated included a unit with both horizontal and vertical construction capability, a unit with only horizontal construction

TABLE 3.13

DUMMY CELLULAR UNITS CREATED TO REMOVE INFEASIBILITIES FROM THE TEST PROBLEM

Dummy Unit Identification	Composition	
	Skill Grouping	Quantity
Survey Team	Surveyor	1
	Rodman-Tapeman	2
Quarry Team	Quarry Operations	27
	Powderman	1
	Crane Operator	4
	Loader Operator	8
	Heavy Dump Trk.Operator	4
	Engr. Equip. Repairman	4
	Construction Helper	2
Diving Team	Diver	9
Electrician Team	Electrician	12
Carpenter Team	Carpenter	12
Pipeline Team	Pipeline Specialist	12
Plumber Team	Plumber	12
Heat & Vent Team	Heat & Vent Specialist	12
Rigger Team	Rigger	12
Pile Driving Team	Pile Driver Operator	12
Truck Driving Team	Medium Truck Driver	12
Constr. Helper Team	Construction Helper	12
Mason Team	Mason	12
Refrigeration Spec. Team	Refrigeration Specialist	12
Ditch. Machine Operator	Ditching Machine Operator	1
Constr. Helper Company	Construction Helper	100
Welding Team	Welder	4

TABLE 3.14

OPTIMAL TROOP UNIT LEVELS FOR GENERAL CONSTRUCTION SUPPORT WITH CELLULAR UNIT AUGMENTATION

Engineer Troop Unit	Quantity of Troop Units Required D-Day to D+30	D+30 to D+60	D+60 to D+90	D+90 to D+120
Combat Battalion	2.3	0	7.6	4.0
Construction Battalion	8.9	17.5	12.2	13.3
Light Equipment Company	0	0	0	0
Constr. Support Company	3.0	3.3	0	0
Dump Truck Company	0	0	0	0
Port Constr. Company	0.1	4.4	3.0	0
Pipeline Constr.Spt.Co.	0	0.6	0	0
Quarry Team	0.2	0	0	0
Diving Team	0	0.4	0	0
Electrician Team	27.1	0	23.4	16.5
Carpenter Team	102.2	265.0	311.0	179.2
Pipeline Team	89.3	35.3	32.1	22.9
Plumber Team	52.1	0	33.4	37.9
Survey Team	24.1	143.9	122.0	118.6
Construction Helper Team	254.1	501.8	372.5	400.1
Heat &Vent Team	0	1.4	0	0
Rigger Team	0.9	14.5	1.6	1.1
Pile Driving Team	1.0	5.6	4.8	0
Truck Driving Team	15.4	16.6	15.1	15.5

TABLE 3.15

TOTAL MANHOURS REQUIRED VERSUS TOTAL EFFECTIVE MANHOURS AVAILABLE AT OPTIMAL TROOP UNIT LEVELS WITH CELLULAR UNIT AUGMENTATION (1000 MANHOURS)

Total Manhours	D-Day to D+30	D+30 to D+60	D+60 to D+90	D+90 to D+120
Available	2633.277	4324.014	4217.800	3607.405
Minimum Required	2107.284	3597.584	3448.018	2934.310

TABLE 3.16

SURPLUS CONSTRUCTION CAPABILITY AT OPTIMAL TROOP UNIT LEVELS WITH CELLULAR UNIT AUGMENTATION (1000 MANHOURS)

Skill	Surplus Construction Capability			
	D-Day to D+30	D+30 to D+60	D+60 to D+90	D+90 to D+120
Foreman (Horiz)	25.972	45.483	44.013	37.873
Surveyor	0	0	0	0
Rodman-Tapeman	2.065	8.925	11.593	12.359
Quarry Opns.	0	28.828	14.231	12.516
Powderman	5.393	9.426	6.975	5.683
Asphalt Opns.	0	25.176	10.582	16.143
Concrete Production	10.342	21.559	15.180	15.345
Crane Op.	6.277	0	0	32.032
Grader Op.	13.575	0	6.402	0.101
Tractor Op.	44.652	3.231	11.152	0
Loader Op.	40.695	58.724	78.925	63.466
Air Comp. Op.	27.334	41.531	34.584	41.234
Ditch. Mach. Op.	2.157	6.474	1.353	2.046
Power Roll. Op.	10.198	13.644	7.816	7.428
Water Dist. Op.	6.684	14.793	11.309	10.466
Hoist Op.	0	2.400	2.335	0
Pile Dr. Op.	0	0	0	0
Pipeline Sp.	0	0	0	0
Hvy. Dump Trk. Op.	61.617	42.824	94.017	76.810
Light-Med. Trk. Dr.	0	0	0	0
Hvy. Veh. Dr.	44.007	105.351	61.308	62.044
Engr. Equip. Rpmn.	134.135	199.216	149.602	141.072
Draftsman	10.265	18.565	14.079	12.523
Welder	19.002	0	31.792	28.717
Foreman (Vert.)	0	6.802	0	0
Carpenter	0	0	0	0
Structures Sp.	12.975	8.969	64.629	40.198
Electrician	0	18.224	0	0
Plumber	0	31.668	0	0
Mason	40.310	11.610	76.836	44.979
Heat & Vent Sp.	2.850	0	10.048	6.148
Refrig. Sp.	5.156	2.935	4.526	3.913
Diver	0.210	0	6.494	0
Rigger	0	0	0	0
Constr. Helper	0	0	0	0

capability, and a unit with only vertical construction capability. These three dummy units were then added to the original Engineer Troop Unit production set.

The skill mix in each of these dummy units was obtained using ratios proportionate to construction requirements ratios. Each skill level was based on the ratio of that skill manhour requirement to total manhour requirements. For dummy horizontal construction units, each horizontal skill level was based on the ratio of that skill manhour requirement to total horizontal manhour requirements. Similarly, vertical formulation was based on total vertical manhour requirements. Results from the initial solution obtained using this approach are shown in Tables 3.17, 3.18, and 3.19.

The structure of the three dummy units was changed for each phase of the problem since it was based on requirements which changed with each phase. The structure used for phase two (D+30 to D+60) is shown in Table 3.20.

A third approach to solving the problem was to add to both cellular units and dummy Battalion sized units to the production set. Results obtained with this approach are shown in Tables 3.21 and 3.22.

It should be noted that the initial solutions were obtained without any binding constraint by force levels and mix. The force levels used for the initial solution were purposely chosen sufficiently high for this test in order to obtain a solution which could then be subjected to

TABLE 3.17

OPTIMAL TROOP UNIT LEVELS FOR GENERAL CONSTRUCTION SUPPORT WITH BATTALION SIZED UNIT AUGMENTATION

Engineer Troop Unit	Quantity of Troop Units Required			
	D-Day to D+30	D+30 to D+60	D+60 to D+90	D+90 to D+120
Combat Battalion	0.2	0.2	0.4	1.0
Construction Battalion	0.2	2.5	0.9	0.8
Light Equipment Company	0	0	0	0
Constr. Support Company	0	0	0	0
Dump Truck Company	0	0	0	0
Port Constr. Company	0.1	0.6	0.2	0
Pipeline Constr.Spt.Co.	0	1.8	1.1	0
Horiz. & Vert.Constr.Unit	2.2	0	2.3	2.8
Horiz. Constr. Unit	7.9	13.8	10.8	8.8
Vert. Constr. Unit	8.0	14.9	15.2	11.5

TABLE 3.18

TOTAL MANHOURS REQUIRED VERSUS TOTAL EFFECTIVE MANHOURS AVAILABLE AT OPTIMAL TROOP UNIT LEVELS WITH BATTALION SIZED UNIT AUGMENTATION (1000 MANHOURS)

Total Manhours	D-Day to D+30	D+30 to D+60	D+60 to D+90	D+90 to D+120
Available	2303.266	3952.092	3696.398	3100.154
Minimum Required	2107.284	3597.584	3448.018	2934.310

TABLE 3.19

SURPLUS CONSTRUCTION CAPABILITY AT OPTIMAL TROOP UNIT LEVELS WITH BATTALION SIZED UNIT AUGMENTATION (1000 MANHOURS)

Skill	Surplus Construction Capability			
	D-Day to D+30	D+30 to D+60	D+60 to D+90	D+90 to D+120
Foreman (Horiz)	8.973	23.323	15.093	9.780
Surveyor	0	0.293	1.490	0.757
Rodman-Tapeman	2.553	5.636	4.460	0
Quarry Opns.	3.404	2.615	1.447	0.506
Powderman	0.089	5.190	4.909	4.238
Asphalt Opns.	3.353	2.173	0.050	3.818
Concrete Production	0.233	8.116	1.147	0.915
Crane Op.	4.778	10.645	6.482	2.155
Grader Op.	3.702	9.219	5.465	4.373
Tractor Op.	17.687	44 412	26.472	17.974
Loader Op.	4.985	14.964	10.477	12.195
Air Comp. Op.	0	8.349	2.913	6.805
Ditch. Mach. Op.	0	4.721	0	0.038
Power Roll. Op.	0.148	2.133	1.414	0.228
Water Dist. Op.	0.035	2.791	1.321	0
Hoist Op.	3.844	4.805	0.176	0
Pile Dr. Op.	0.070	0	0	0
Pipeline Sp.	35.685	22.044	17.924	1.412
Hvy. Dump Trk. Op.	10.642	28.133	18.219	18.552
Light-Med. Trk Dr.	6.217	6.762	5.929	0.814
Hvy. Veh. DR.	3.474	17.252	7.474	3.658
Eng. Equip. Rpmn.	4.185	37.491	19.587	15.916
Draftsman	0.402	3.480	0	0.787
Welder	1.222	13.979	9.936	6.199
Foreman (Vert)	0.322	9.070	4.884	5.649
Carpenter	0	0	0	0
Structures Sp.	0.790	5.081	5.247	6.180
Electrician	0.858	12.301	2.577	3.702
Plumber	0.140	12.878	3.996	2.956
Mason	1.349	6.041	3.037	10.548
Heat & Vent. Sp.	0	0	0	0
Refrig. Sp.	0.107	0	4.715	0
Diver	0.125	0.700	5.604	0
Rigger	0.295	0	0	2.987
Constr. Helper	76.299	29.892	55.920	22.685

TABLE 3.20

MANPOWER FOR DUMMY BATTALION SIZED UNITS USED FOR D+30 to D+60 AUGMENTATION OF STANDARD UNITS

Skill	Dummy Battalion Sized Unit		
	Horizontal & Vertical Capability	Horizontal Capability	Vertical Capability
Foreman (Horiz)	13	28	
Surveyor	6	13	
Rodman-Tapeman	12	27	
Quarry Opns.	2	4	
Powderman	2	2	
Asphalt Opns.	2	4	
Concrete Production	2	2	
Crane Op.	11	25	
Grader Op.	10	23	
Tractor Op.	43	95	
Loader Op.	2	2	
Air Comp. Op.	3	7	
Ditch. Mach. Op.	2	2	
Power Roll. Op.	2	4	
Water Dist. Op.	2	2	
Hoist Op.	2	2	
Pile Dr. Op.	2	6	
Pipeline Sp.	17	37	
Hvy. Dump Trk. Op.	21	47	
Light-Med.Trk. Op.	9	20	
Hvy. Veh. Dr.	3	8	
Engr. Equip. Rpmn.	9	21	
Draftsman	1	3	
Welder	8	19	
Foreman (Vert)	16		30
Carpenter	167		307
Structures Sp.	3		5
Electrician	19		36
Plumber	16		31
Mason	5		10
Heat & Vent Sp.	1		3
Refrig. Sp.	1		2
Diver	2		4
Rigger	7		13
Constr. Helper	227	247	209
Total	650	650	650

TABLE 3.21

OPTIMAL TROOP UNIT LEVELS FOR GENERAL CONSTRUCTION SUPPORT WITH BATTALION SIZED UNIT AND CELLULAR UNIT AUGMENTATION

Engineer Troop Unit	Quantity of Troop Units Required			
	D-Day to D+30	D+30 to D+60	D+60 to D+90	D+90 to D+120
Combat Battalion	0.1	0.1	0	0.2
Construction Battalion	0.7	0.9	1.3	1.2
Light Equipment Company	0	0	0	0
Constr. Support Company	0.2	0	0	0.1
Dump Truck Company	0	0	0	0
Port Constr. Company	0	0.2	0.3	0
Pipeline Constr.Spt.Co.	0	0.2	0	0
Quarry Team	0.1	0	0	0
Diving Team	0	0.4	0	0
Electrician Team	0	0	2.0	1.6
Carpenter Team	1.8	10.8	19.5	12.9
Pipeline Team	4.4	0	2.5	2.2
Plumber Team	1.0	0	1.8	2.8
Survey Team	7.2	9.6	12.1	9.6
Constr. Helper Company	0.5	0.2	2.5	3.2
Heat & Vent Team	0.1	0.9	0.5	0.8
Rigger Team	0	1.4	0.9	0
Pile Driving Team	0.2	1.1	0.7	0
Truck Driving Team	0.9	0.4	1.1	1.3
Horiz. & Vert.Constr.Unit	1.5	10.7	3.9	0
Horiz. Constr. Unit	6.6	8.2	8.8	9.2
Vert. Constr. Unit	8.2	9.1	13.3	12.6
Mason Team	0	0	0.8	0
Refrig. Sp. Team	0	0.4	0	0.3
Ditch Mach. Op.	1.2	0	0	4.2

TABLE 3.22

SURPLUS CONSTRUCTION CAPABILITY AT OPTIMAL TROOP UNIT LEVELS WITH BATTALION SIZED AND CELLULAR UNIT AUGMENTATION (1000 MANHOURS)

Skill	Surplus Construction Capability			
	D-Day to D+30	D+30 to D+60	D+60 to D+90	D+90 to D+120
Foreman (Horiz)	2.211	5.389	3.141	2.195
Surveyor	0	0	0	0.211
Rodman-Tapeman	2.126	3.350	2.568	0
Quarry Opns.	0	0	1.210	0.715
Powderman	0	6.609	4.712	3.214
Asphalt Opns.	0	0.160	0.058	3.785
Concrete Production	0.819	8.226	1.595	1.339
Crane Op.	0.668	0	0	1.676
Grader Op.	0.972	0	0	0
Tractor Op.	5.390	10.303	5.668	2.616
Loader Op.	5.331	10.773	9.075	8.250
Air Comp. Op.	0.953	1.846	2.141	6.218
Ditch. Mach. Op.	0	6.153	0.340	0
Power Roll. Op.	0.344	0	0.656	0
Water Dist. Op.	0	3.056	1.936	0
Hoist Op.	3.023	6.489	0.245	0
Pile Dr. Op.	0	0	0	0
Pipeline Sp.	0	0	0	0
Hvy. Dump Trk. Op.	4.055	7.149	5.335	6.198
Light-Med. Trk. Dr.	0	0	0	0
Hvy. Veh. Dr.	3.735	4.110	6.611	4.542
Eng. Equip. Rpmn.	9.771	11.144	13.944	12.554
Draftsman	0.511	0	0	0.758
Welder	1.832	0	6.437	5.881
Foreman (Vert)	0.712	0	0	0
Carpenter	0	0	0	0
Structures Sp.	0	0	0.184	0
Electrician	0	0.367	0	0
Plumber	0	0.445	0	0
Mason	1.041	0.653	0	1.504
Heat. & Vent. Sp.	0	0	0	0
Refrig. Sp.	0.408	0	4.856	0
Diver	0	0	5.779	0
Rigger	0	0	0	2.306
Constr. Helper	0	0	0	0

more severe constraints. Once initial solutions were obtained, bound levels were set lower than optimal levels and attempts were made to find new solutions within bound and mix constraints. With this approach it was observed that specifying both allocation and bound constraints could over restrict the problem.

A better approach to solving the problem seems to be to eliminate allocation constraints and to set bound levels only on all key units. In this manner, a unit would enter the solution relative to its contribution to production without restriction imposed by some other unit's contribution to production. Tables 3.24 and 3.25 show solutions obtained with bounds as shown in Table 3.[illegible]. Table 3.25 summarizes comparisons between effective manhours available and minimum manhours required using all solution approaches. Table 3.26 shows the effect of removing allocation constraints from the solution shown in Table 3.21.

D. ANALYSIS

1. Problem Solutions

An important outcome of the solutions was the evidence of an obvious shortage of manpower in vertical construction capability and in construction helper (unskilled labor) capability of standard Engineer Units. The results clearly illustrated the major weakness of current methodology of determining troop unit levels on the basis of total manhour calculations. Such calculations would not

TABLE 3.23

BOUNDS CONSTRAINTS ON QUANTITY OF TROOP UNITS ALLOWED IN FINAL SOLUTION

Engineer Troop Unit	Upper Bound
Combat Battalion	8
Construction Battalion	12
Light Equipment Company	8
Construction Support Company	10
Dump Truck Company	5
Port Constr. Company	8
Pipeline Constr. Spt. Company	10
Horiz. & Vert. Constr. Unit	0
Horizontal Constr. Unit	2
Vertical Constr. Unit	6

reveal the nature and extent of the shortage shown by the linear programming model.

Additionally, the linear programming model clearly showed the type and amount of minimum surplus construction capability associated with each solution. With current methodology, this type of information is not known even though it is assumed that there will be sufficient surplus to upgrade facilities and to cover slippages or uncertainties in estimates. The results indicated that there would

TABLE 3.24

OPTIMAL TROOP UNIT LEVELS FOR GENERAL CONSTRUCTION SUPPORT WITH BATTALION SIZED UNIT AND CELLULAR UNIT AUGMENTATION (WITH BOUNDS SHOWN IN TABLE 3.23) (WITH NO ALLOCATION CONSTRAINTS)

Engineer Troop Unit	Quantity of Troop Units Required			
	D-Day to D+30	D+30 to D+60	D+60 to D+90	D+90 to D+120
Combat Battalion	0	0	0	0
Construction Battalion	4.1	12.0	11.6	11.2
Light Equipment Company	1.2	8.0	0.6	0.8
Constr. Support Company	2.8	0	0	0
Dump Truck Company	0	0	0	0
Port Constr. Company	0	3.5	4.9	0
Pipeline Constr.Spt. Co.	0.8	0	0	0
Quarry Team	0.2	0	0	0
Diving Team	0	0	0	0
Electrician Team	8.5	0	12.3	8.2
Carpenter Team	32.6	205.5	187.7	108.3
Pipeline Team	63.7	32.6	32.4	20.8
Plumber Team	17.3	0	18.5	21.8
Survey Team	26.2	129.6	111.6	96.8
Constr. Helper Company	0	48.2	0	0
Constr. Helper Team	149.9	0	334.6	315.4
Heat & Vent Team	0.2	1.3	1.2	0.6
Rigger Team	0	11.2	0	0.3
Pile Driving Team	0.8	4.9	3.6	0
Truck Driving Team	11.3	15.2	13.1	12.9
Horiz.& Vert.Constr.Unit	0	0	0	0
Horiz. Constr. Unit	2.0	2.0	1.2	2.0
Vert. Constr. Unit	6.0	4.0	6.0	4.7
Mason Team	0	0	0	0
Refrig. Sp. Team	0	0	0	0
Ditch. Mach. Op.	0	0	0	0
Welding Team	0	8.4	0	0

TABLE 3.25

TOTAL MANHOURS REQUIRED VERSUS TOTAL EFFECTIVE MANHOURS AVAILABLE AT OPTIMAL TROOP UNIT LEVELS WITH BATTALION SIZED UNIT AND CELLULAR UNIT AUGMENTATION (1000 MANHOURS)

Total Manhours	D-Day to D+30	D+30 to D+60	D+60 to D+90	D+90 to D+120
Available[1]	2633.277	4324.014	4217.800	3607.405
Available[2]	2279.443	4148.562	3908.711	3377.279
Available[3]	2303.266	3952.092	3696.398	3100.154
Available[4]	2151.240	3683.892	3524.517	2998.289
Available[5]	2141.878	3683.892	3516.674	2998.289
Min.Required	2107.284	3597.584	3448.018	2934.310

[1]Cellular unit augmentation only with bounds and allocations as shown in Table 3.6.

[2]Cellular unit and Battalion sized unit augmentation with bounds as shown in Table 3.23 and no allocation constraints.

[3]Battalion sized unit augmentation with bounds and allocations as shown in Table 3.6.

[4]Cellular unit and Battalion sized unit augmentation with bounds and allocations as shown in Table 3.6.

[5]Cellular unit and Battalion sized unit augmentation with bounds as shown in Table 3.6 and no allocation constraints.

TABLE 3.26

OPTIMAL TROOP UNIT LEVELS FOR GENERAL CONSTRUCTION SUPPORT WITH BATTALION SIZED UNIT AND CELLULAR UNIT AUGMENTATION (WITH BOUNDS SHOWN IN TABLE 3.6 AND NO ALLOCATION CONSTRAINTS)

Engineer Troop Unit	Quantity of Troop Units Required			
	D-Day to D+30	D+30 to D+60	D+60 to D+90	D+90 to D+120
Combat Battalion	0.1	0.1	0	0.2
Construction Battalion	0.4	0.9	1.0	1.2
Light Equipment Company	1.0	0	0.6	0
Constr. Support Company	0.5	0	0	0.1
Dump Truck Company	0.1	0	0	0
Port Constr. Company	0	0.2	1.2	0
Pipeline Constr.Spt.Co.	0	0.2	0	0
Quarry Team	0	0	0	0
Diving Team	0	0.4	0	0
Electrician Team	0	0	2.7	1.6
Carpenter Team	1.2	10.8	21.2	12.8
Pipeline Team	9.7	0	3.4	2.2
Plumber Team	0.5	0	2.6	2.8
Survey Team	10.1	9.7	15.4	9.6
Constr. Helper Team	10.7	2.0	3.5	27.0
Heat & Vent. Team	0.1	0.9	0.6	0.8
Rigger Team	0	1.4	0.3	0
Pile Driving Team	0.2	1.1	0.5	0
Truck Driving Team	2.0	0.4	1.2	1.3
Horiz. & Vert.Constr.Unit	1.6	10.7	0	0
Horiz. Constr. Unit	6.1	8.2	9.9	9.2
Vert. Constr. Unit	8.3	9.1	15.6	12.6
Mason Team	0	0	0.7	0
Refrig. Sp. Team	0	0.4	0	0.3
Ditch Mach. Op.	0	0	3.5	4.2

be little surplus vertical construction capability above that required for minimum essential tasks.

It should also be noted that the initial feasible solutions were obtained only by assuming availability of some type of augmentation for standard units. Entering dummy units into the production set provides a basis for controlling assumptions usually made in current methodology concerning augmentation of standard Engineer Troop Unit and meeting requirements with use of indigenous forces. The dummy units used in the solutions could be assumed to be purely military units, units with military and indigenous labor mix, or purely indigenous units. Such units could also represent contract capability if U.S. contractor forces are admitted to the operations.

The series of solutions presented amplify the point that a range of solutions can be obtained contingent upon planner assumptions and policy restrictions. An important aspect of the model is that the effect of such assumption and policy restriction can be delineated.

It is possible to derive troop levels such that total effective manhours available very closely matches requirements. If the operation is conducted over a long time frame these levels could be used to specify time phased troop requirements. If effective manhours match requirements and there is still a requirement to upgrade facilities, the additional work could be introduced as a bonafide

requirement rather than as an assumption. This would increase data requirements and would increase planner effort to derive the added project lists, but the return would be a better understanding and development of force requirements.

Another factor to consider in evaluating the solutions presented is whether or not the true solution to the problem should be integer valued. The test problem only considered general construction requirements whereas troop units such as Engineer Combat Battalions may also be required for other tasks. If this is true then a fractional quantity of such units may really be required for general construction support. However, requirements for troop units whose sole task is general construction support should be integer valued. If one desires to find optimal solutions which are integer valued then integer programming techniques, such as those proposed by Gomory [18], should be used.

Integer valued solutions may be quite different from those obtained by rounding fractional solutions. Whether integer valued solutions would be any better is questionable if maximum values obtained during any one time phase are chosen as the desired solution for all time phases. Furthermore, one cannot arbitrarily round off the values given to integers and retain assurance that they represent feasible solutions to the problem.

2. Model Advantages and Disadvantages

The test problem revealed several advantages and disadvantages of the model. One principal advantage is the

improved information and problem control obtained. In addition, it should greatly reduce manual calculating effort and time and thereby permit the planner to place more effort on determining requirements and evaluating the effect of assumptions.

The ability to quickly change a set of assumptions and resolve problems is an advantage not enjoyed by present methodology. This advantage of the model can permit not only better evaluation of any one solution but also permits wider analysis of alternate solutions.

The model also has an ability to evaluate the influence of allocation constraints. The removal of allocation constraints permits each competing engineer troop unit to enter the solution solely on the basis of its relative effectiveness in the given situation. In this manner the suitability of allocation rules can be examined by comparing solutions obtained with and without allocation constraints.

The methodology used in solving the test problem was designed also to indicate the model's adaptability to real time remote terminal computer applications. Although the primary data for force development planning could be very large, the data requirements for a given problem should not be excessively large. By extracting data from a main data base one can form data suitably sized for terminal operations. This approach was taken in solving the test problem and proved to be extremely valuable since it

provided considerable flexibility for changing control variable and parameter values and in evaluating results.

In general, the test problem showed that the model could provide reasonable solutions to the problem of determining the proper level, mix, and balance of engineer forces required to support given theater requirements subject to manpower and policy constraints. It accounted for a wide range of planner assumptions and provided a means for evaluating the influence of these assumptions on the solution. Offsetting its complexity is the reduction in time required to develop solutions and the greater information and insight it provides to the force planning problem over the existing approach.

A disadvantage of the model is that it introduces more complexity into the calculating process than the current approach. The current methodology is quite simple and can be accomplished manually whereas the model requires a simultaneous solution to a large set of equations which cannot be easily solved manually.

Another disadvantage is the data requirement. As a minimum, the model should have access to three sets of data. These are installation facility requirements, facility manhour requirements by skill grouping, and Engineer Unit manpower by skill grouping. The Engineer manpower data requirement is no serious problem. The other requirements are.

This disadvantage is partially offset by the fact that installation facility requirements data has already been developed for computer application in the Engineer Functional Components System. Facility manhour requirements by skill grouping data has not been developed, but essential information is available in labor and equipment summaries which could be updated and published as an extension of the Engineer Functional Components System. The seriousness of the facility manhour requirements data development is dependent on the intended level of usage.

If one desires a complete data base for world wide application, such as the Engineer Functional Components System, then the effort required to develop the data will be large. On the other hand, such data could be developed in stages as it is required for given force development problems. For each successive problem solved, new data could be developed as required and added to a growing data base. Thus the data base would be developed and updated as required over a period of time. It could eventually evolve into a base comparable with the Engineer Functional Components System.

Another possible disadvantage of the model is that it is not a closed model for solving for force level, mix, and balance. It is not closed in that the planner must evaluate the output and make changes as necessary to derive acceptable overall solutions. The model is intended to assist the planning process and, in particular, to serve as

a calculating aid to the planner and not to replace him. That the model requires interface with a planner for most profitable use is not a serious disadvantage since the final solution to the problem will enjoy the benefits of planner ability to make judgments and decisions, and the model ability to accurately calculate and relate these judgments and decisions.

IV. ALTERNATE FORMULATIONS AND EXTENSIONS

A. POLICY CONSTRAINTS

The formulation described in Chapter II can be extended to account for policy constraints pertaining to standards of construction, priorities and/or allowable percentages of construction. The Engineer Functional Components System codes installations and facilities in terms of general categories of construction and, additionally, codes installations in terms of standards of construction. Policy constraints relating to standards of construction would be satisfied by either limiting the F matrix elements to appropriate standards of construction or by extracting from the F matrix only that portion that satisfies standards constraints.

Priorities of construction and/or allowable percentages of construction can be identified with general categories of construction which in turn can be related to specific facilities. The requirements vector can be obtained for this case by first changing the previously defined P, Q, and D vectors from facilities "required" to facilities "desired" subject to allowable percentages of construction. For a given phase, Q would be calculated as previously described. One can then form: a t x t matrix, A_p, with diagonal elements representing the allowable percentage for construction of a given facility during a given time phase,

and zeros for all other elements; a column vector, B, of order t, whose entries would be the difference between the quantity of facilities "desired" and "allowed" for construction within a given time period; a column vector, Q_a, of order t, whose entries would be the quantity by type of facilities "allowed" for construction within a given time period; and a column vector, M, of order t, whose entries would represent the total construction requirement for a given time period.

For the first phase of an operation, B could represent construction which had been in progress and must be finished for support of the operation, or it could represent carry-over construction which had not been allowed for a previous period. On the other hand, Q would be new construction support required for the time period currently being considered. The total construction requirement for the current period would be expressed by the vector sum

$$M = B + Q.$$

By specifying the matrix A_p in consonance with allowable percentages of construction, allowable construction would be the matrix product

$$Q_a = A_p M,$$

and the product

$$W = \lambda R Q_a$$

would provide the production requirements vector for the given time period of the operation. The vector difference

$$B = M - Q_a$$

would provide carryover construction requirements for the next succeeding time period. Repetition of these calculations would provide the appropriate requirements vector for each specified time period of the operation.

B. COST FUNCTIONS

It is possible that planning objectives may be formulated to provide forces at least cost yet meet operational requirements. The model can also satisfy this objective if suitable cost coefficients are developed for the objective function. For minimum cost functions the form would be $E'X$ where E' is an effectiveness coefficient row vector of order n, $(e'_1, e'_2, \ldots, e'_n)$, whose elements would be effective production labor costs for each Engineer Troop Unit. Other elements of the model would remain unchanged from the description given in Chapter II.

If a solution is acceptable only if it satisfies given labor budget constraints then this aspect could be incorporated by adding another constraint of the form

$$E'X \leq b,$$

where b represents the total dollar labor cost budget ceiling, could be added to the model.

To determine total labor and material costs, overhead costs and material costs would have to be developed. Material costs for installations and facilities are published in the Engineer Functional Components System. Material costs for damage repair and renovation or use of indigenous resources are not published but would have to be developed if such activities are part of production requirements. Overhead costs for standard engineer units could be developed from the tables of organization and equipment. Similar costs for cellular units or dummy units used in solutions would have to be developed to fit the given situation.

C. PRODUCTION FUNCTIONS

Another alternate planning objective may be to provide maximum production for a given set of Engineer forces. The model can also satisfy this objective with a minor change in structure. For this objective the model takes the form

$$\begin{aligned} \text{maximize} \quad & Z = IY, \\ \text{subject to} \quad & R'Y \leq W^*, \\ & IY \geq N, \\ & Y \geq 0, \end{aligned}$$

where

Z = total number of projects.

I = an n x n identity matrix.

Y = a column vector of order n, $(y_1, y_2, \ldots, y_n)$, whose elements represent unknown quantities of project type j.

R' = an $m \times n$ matrix of project production requirements whose elements, r'_{ij}, represent skill i manhours for each project j.

W^* = a column vector of order m, $(w_1^*, w_2^*, \ldots, w_m^*)$, whose elements represent manhour production capability by skill grouping i for a given mix of Engineer units.

N = a column vector of order n, $(n_1, n_2, \ldots, n_n)$, whose elements represent minimum project requirement levels.

This formulation has a direct relationship to the model described in Chapter II. The procedures used to solve that problem apply directly to the solution of this new problem.

Consider the notation and concepts of Chapter II. The production constraint set was $SX \geq W$ which can be expanded for derivation of parameters to the relationship

$$SX \geq \lambda RQ.$$

In this form, the unknown in the original formulation was the vector X. The matrices S and R were fixed by some estimating technique, the scalar λ was fixed, and the vector Q represented a given list of facility requirements.

With the new formulation, the vector X becomes fixed and the vector Q becomes the unknown. Notation is changed in the new formulation because the requirements were originally formulated as a mix of installations and facilities. This mix was reduced by matrix operations to the vector Q. Merely reversing this process would not be suitable because it should be necessary to construct complete installations and

not merely a group of unrelated facilities. The matrix R in the original formulation only related manhour requirements by skill grouping to facilities whereas the matrix R' represents manhour requirements by skill grouping for both facilities and installations.

Such a matrix can be derived by simple operations on the data established for the original problem. The R' matrix should be reduced to a size commensurate with anticipated types of projects required and then solutions can be sought for quantities of such types which can be produced. The vector Y thus can represent installation and facility mix unknowns.

The remaining parameters can be specified by setting

$$W^* = SX$$

using the S matrix from the original problem and the X vector as given. With N, R', and W* specified, the problem can be solved with linear programming solution techniques. In this case integer programming techniques should be used since fractional quantities of projects would have no real meaning.

D. EXTENSIONS

1. Force Level and Requirements Calculating Methodology

The ability of the basic model to quickly adapt to either a minimization problem for solution of force levels given a project mix, or to a maximization problem for solution of project mix given force levels, provides a

calculating concept to improve or extend current force planning methodology. Current methodology is to solve for force levels given a project mix, then choose the maximum levels obtained and use surplus capability to satisfy uncertainties and/or upgrade facilities to higher construction standards. In reality, current methodology only solves one part of the problem, namely force levels for a given project mix. It is then assumed that these forces can accomplish the additional requirements.

Contrast this with the ability to be able to successively solve both problems. Suppose the planner first establishes minimum essential construction requirements for each phase of the operation and uses the model to solve for force levels based on these requirements. He then evaluates the solution, chooses his force levels by taking maximum levels over the entire operation and then readdresses the problem with these forces as given. He can now turn to the maximization capability of the model and, using these forces, determine what installations and facilities can be constructed subject to production capability and some set of minimum requirements. Columns in the R' matrix can represent manhour requirements to upgrade facilities or new projects as well as the required types of projects. With this approach the planner can ascertain not only whether he has selected his forces properly but can examine also the nature and extent of additional construction that could be accomplished.

2. Construction Requirements Analysis

With the ability of this model to quickly evaluate forces and requirements, major changes in constraints can be made and solutions obtained for analysis. As a prime example, consider project mix requirements. The model addresses the problem based on the assumption that the project mix is given. In essence, so does the planner under current methodology. If the planner is faced with an arbitrary ceiling on troop unit levels, should he necessarily assume the project mix to be fixed? It could happen that the general planner specifies a workload and then limits the forces such that the workload can't be reasonably accomplished. In these cases the engineer planner could propose tradeoffs since he could readily evaluate tradeoffs within the project mix as well as substitutions for the project mix. With the ability to calculate project mix given a force structure, the engineer planner could ascertain what could be done within arbitrary force ceilings.

Similar evaluations could be made for major changes in installation or facility design. For example, the test problem was predicated on use of wood structures. This influenced the skill mix and level requirements for vertical construction skills. By alternating between the two forms of the model, the planner could introduce alternate types of construction, i.e., steel, concrete, or indigenous types, and evaluate tradeoffs with types of construction specified

in the Engineer Functional Components System and established in the basic data.

3. Troop Unit Structure Analysis

The flexibility for introducing dummy units into the production set provides a capability for evaluating troop unit structure. For example, one column in the production set could represent a standard unit as currently configured, another column could represent augmentation of such a unit, and another column could represent some proposed unit. If one had a large number of random samples of project mixes, the model could be used to derive a family of solutions. Since the model in essence solves for troop unit levels on the basis of their relative effectiveness, the solutions would show the relative effectiveness of the opposing units over a range of anticipated utilization. Combining this with statistical evaluation techniques, one could determine if there were significant differences in the effectiveness of the units being compared. Such comparisons could not necessarily be used to precisely measure the effectiveness of any one unit, but should provide a means for ranking the units in terms of relative effectiveness.

A more viable application would be the evaluation of cellular team concepts and concepts of indigenous labor augmentation of standard units. It is doubtful that any one standard unit can be structured to satisfy all possible construction requirements under all possible conditions. Such units can, however, be conceived as a nucleous which

could be readily available for any circumstances. Construction forces for given theaters could then be designed with the standard units as a nucleous augmented by other forces such as cellular teams and indigenous labor units.

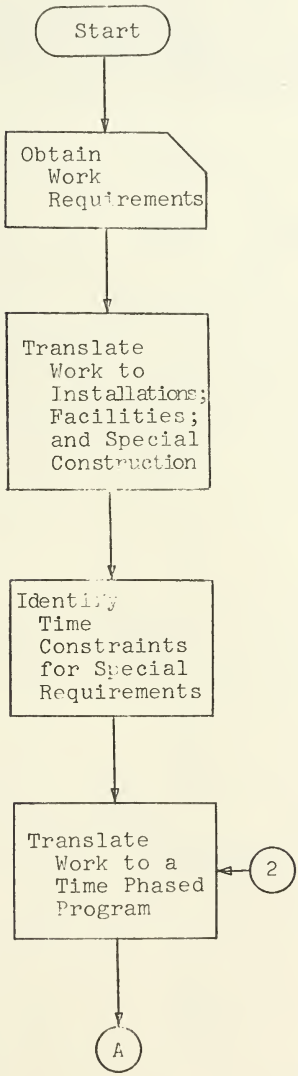
By evaluating suitable random project mixes for various theaters, it should be possible to determine the requirements for and configuration of cellular teams and U.S. support requirements for indigenous forces. It is not presumed that this would be an easy task since the results would be driven by the assumed project mixes and estimates of construction requirements and troop unit construction capabilities. Such analysis could be undertaken if acceptable data is developed.

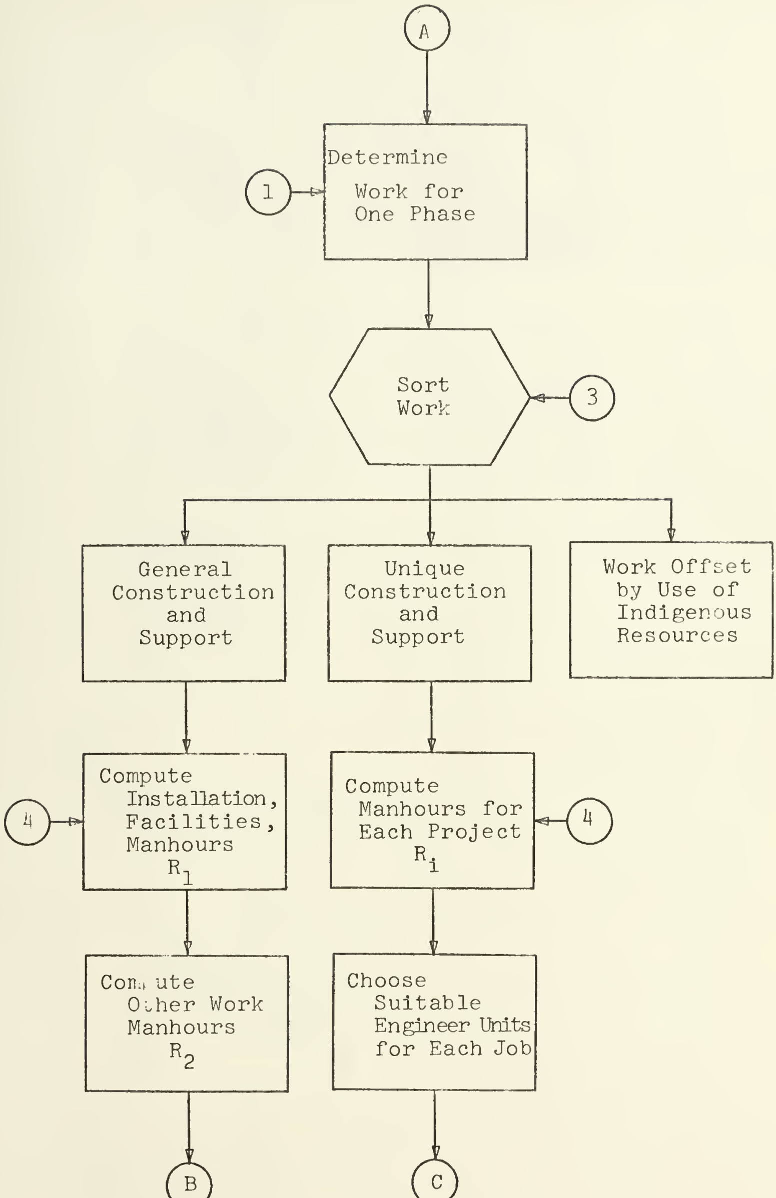
The model also provides a basis for evaluating allocation constraints. The simple test problem used in this paper showed that better results could be obtained if allocation constraints were removed. This problem, however can, at best, be conceived only as one arbitrary sample which is not sufficient for an adequate appraisal of allocation rules. Given a wide range of such solutions, however, one could determine whether such constraints were really in consonance with operations objectives.

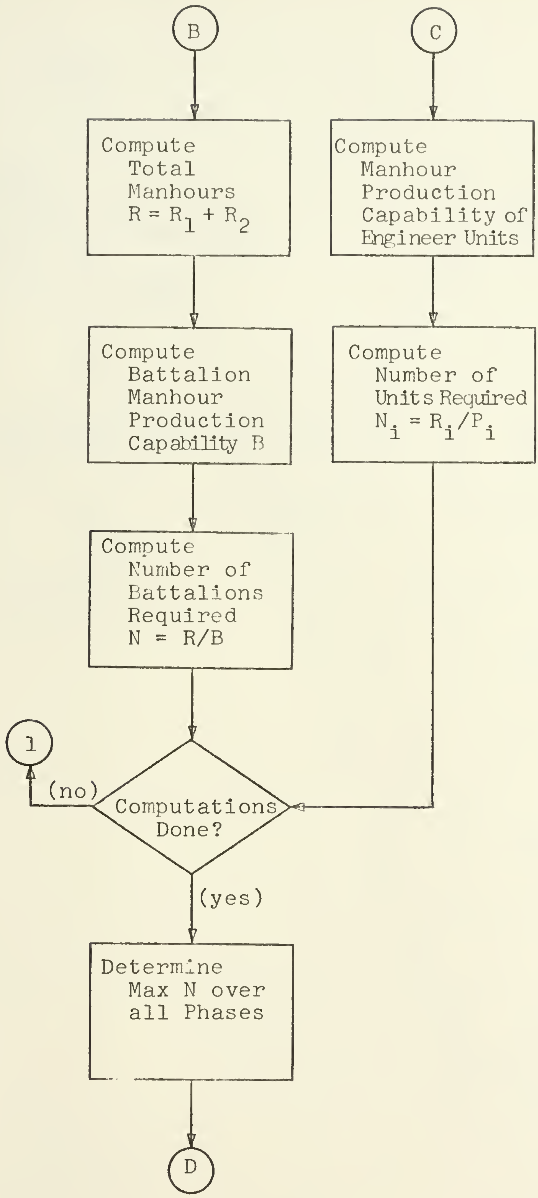
These extensions show that with suitable application the model can help free the planner from manual calculation effort and permit deeper investigation into the matters which, in reality, drive the solutions.

APPENDIX A

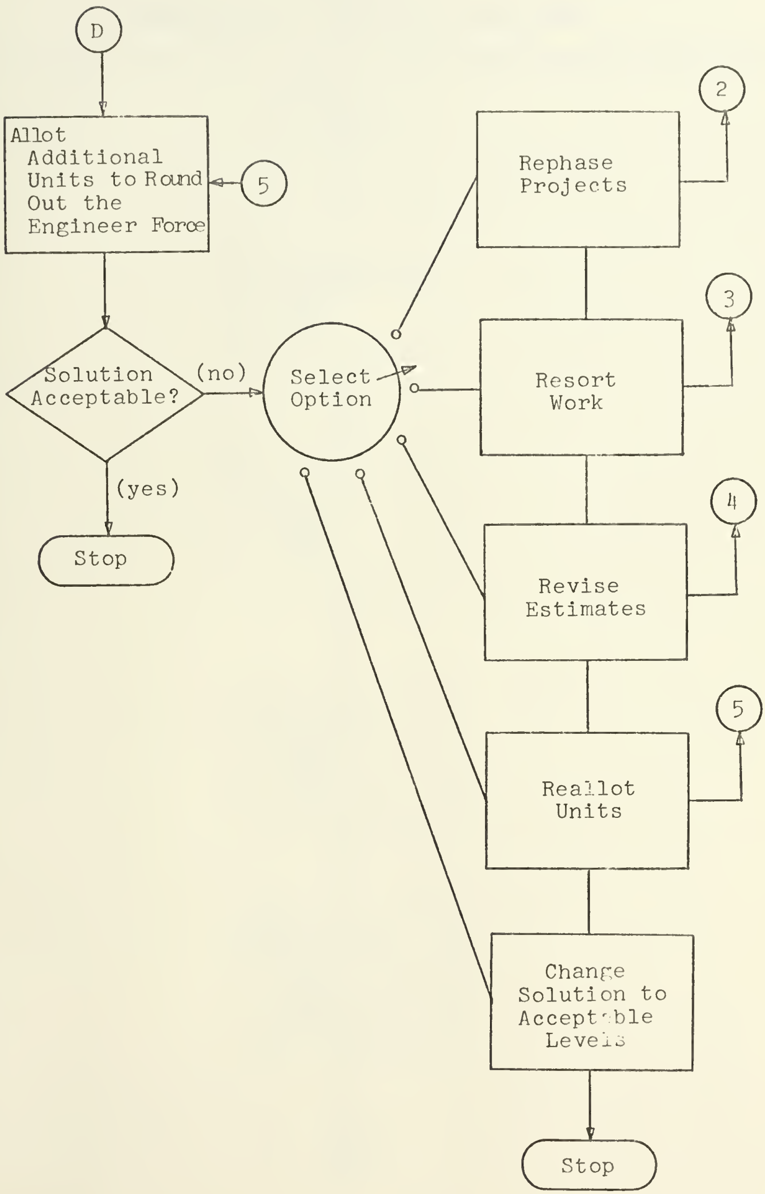
FLOW DIAGRAM FOR CURRENT WORKLOAD
METHODOLOGY WORKLOAD




A
1
Determine Work for One Phase
Sort Work
3
General Construction and Support
Unique Construction and Support
Work Offset by Use of Indigenous Resources
4
Compute Installation, Facilities, Manhours R_1
Compute Manhours for Each Project R_i
4
Compute Other Work Manhours R_2
Choose Suitable Engineer Units for Each Job
B
C



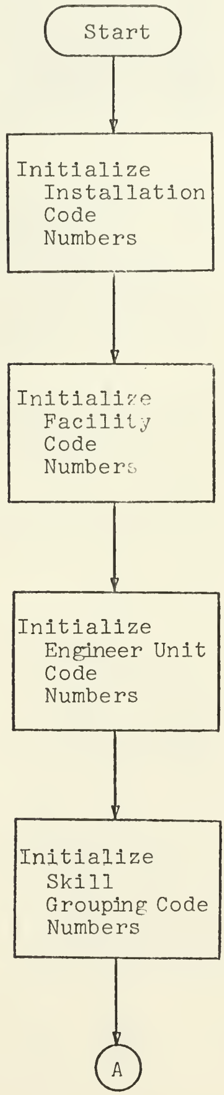
B
C
Compute Total Manhours $R = R_1 + R_2$
Compute Manhour Production Capability of Engineer Units
Compute Battalion Manhour Production Capability B
Compute Number of Units Required $N_i = R_i/P_i$
Compute Number of Battalions Required N = R/B
1
(no)
Computations Done?
(yes)
Determine Max N over all Phases
D

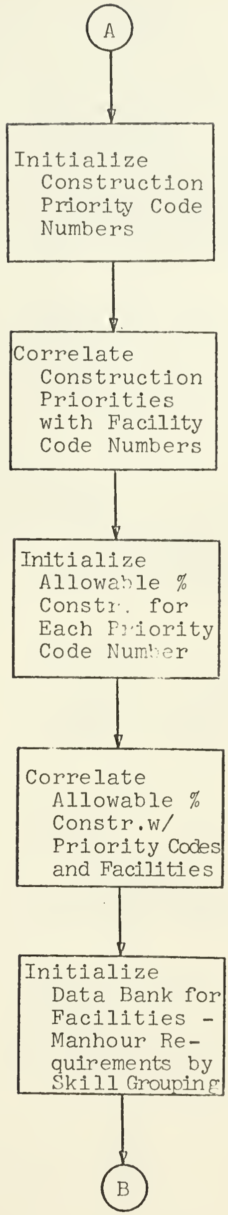

D
Allot Additional Units to Round Out the Engineer Force
5
Solution Acceptable?
(no)
(yes)
Stop
Select Option
Rephase Projects
2
Resort Work
3
Revise Estimates
4
Reallot Units
5
Change Solution to Acceptable Levels
Stop

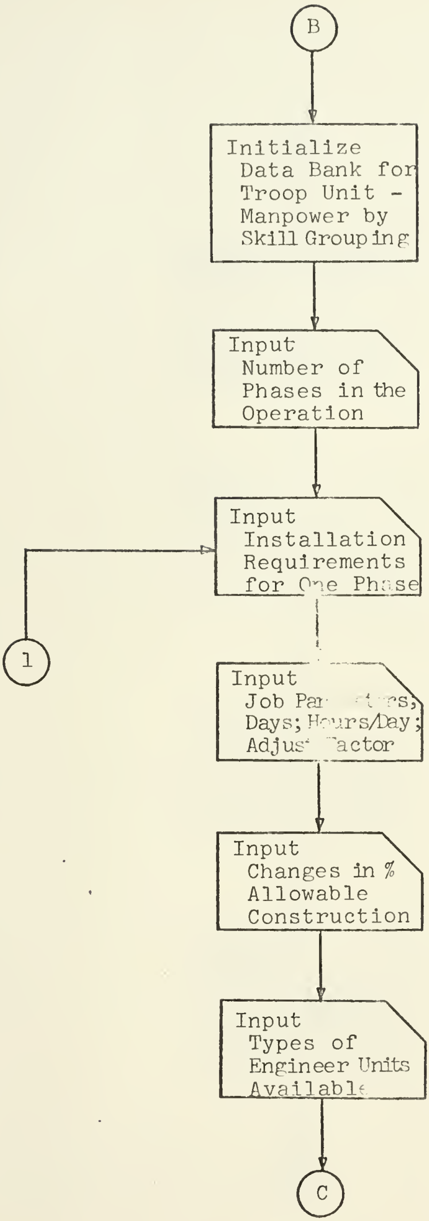
APPENDIX B

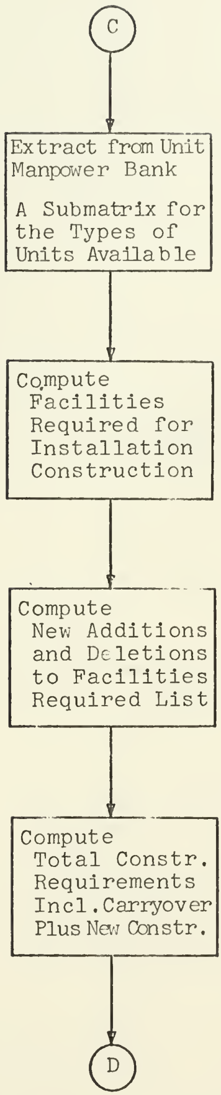
COMPUTATIONAL PROCEDURE FLOW CHART

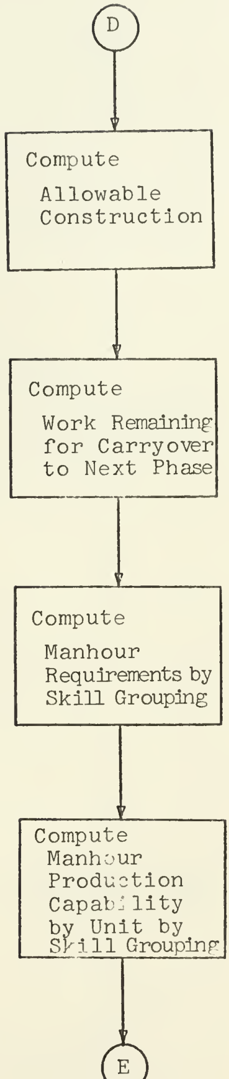
1. Program 1 - Data Bank Initialization and Initial Computations.

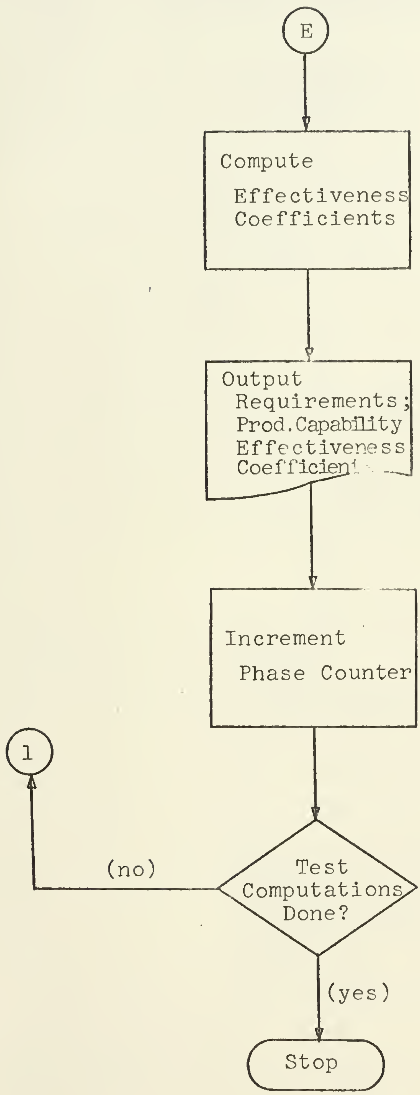



A
Initialize Construction Priority Code Numbers
Correlate Construction Priorities with Facility Code Numbers
Initialize Allowable % Constr. for Each Priority Code Number
Correlate Allowable % Constr.w/ Priority Codes and Facilities
Initialize Data Bank for Facilities - Manhour Requirements by Skill Grouping
B

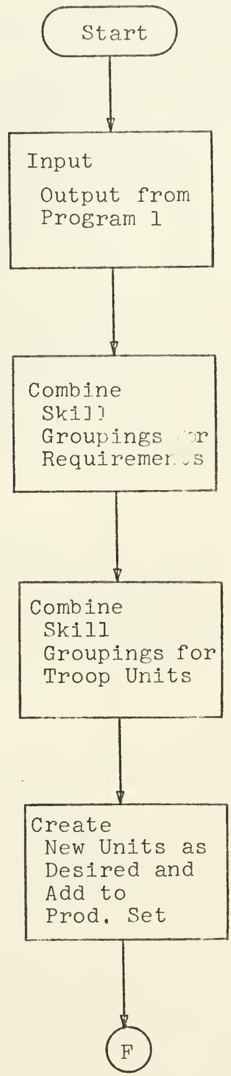

B
Initialize Data Bank for Troop Unit - Manpower by Skill Grouping
Input Number of Phases in the Operation
Input Installation Requirements for One Phase
1
Input Job Par
Days;
Adjus
Input Changes in % Allowable Construction
Input Types of Engineer Units Availabl
C

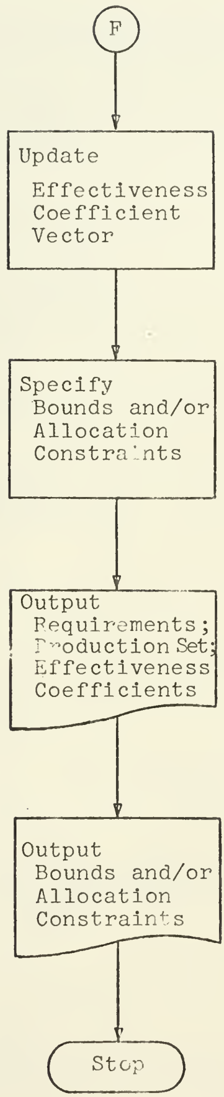

C
Extract from Unit Manpower Bank
A Submatrix for the Types of Units Available
Compute Facilities Required for Installation Construction
Compute New Additions and Deletions to Facilities Required List
Compute Total Constr. Requirements Incl. Carryover Plus New Constr.
D


D
Compute Allowable Construction
Compute Work Remaining for Carryover to Next Phase
Compute Manhour Requirements by Skill Grouping
Compute Manhour Production Capability by Unit by Skill Grouping
E

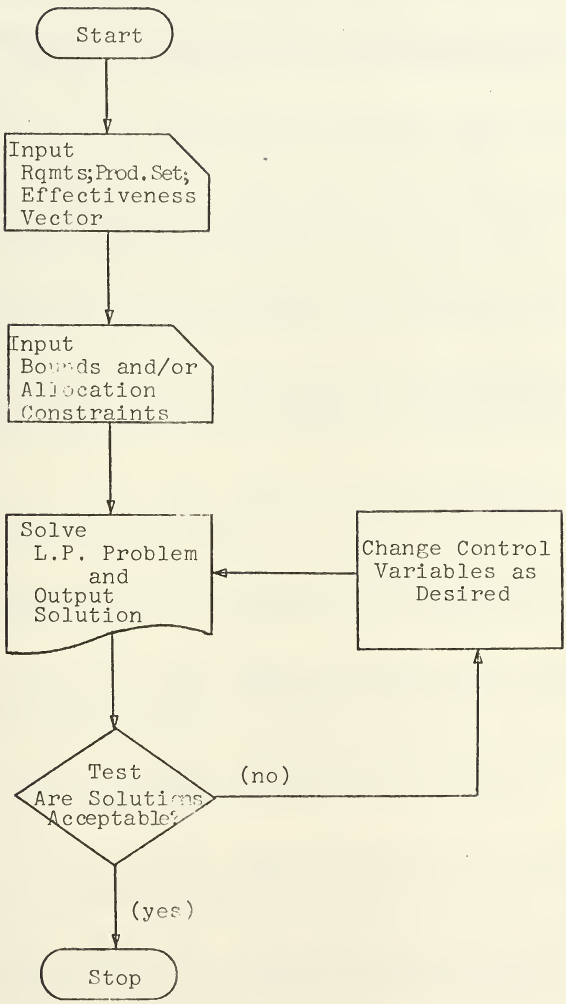

E
Compute Effectiveness Coefficients
Output Requirements; Prod. Capability Effectiveness Coefficients
Increment Phase Counter
Test Computations Done?
(no)
1
(yes)
Stop

2. Program 2 - Additional Calculations and Specification of Control Parameters.




F
Update Effectiveness Coefficient Vector
Specify Bounds and/or Allocation Constraints
Output Requirements; Production Set; Effectiveness Coefficients
Output Bounds and/or Allocation Constraints
Stop

3. Program 3 - Linear Programming Solution Model.



BIBLIOGRAPHY

1. Department of the Army Field Manual, FM 101-10-1, Staff Officers' Field Manual Organization, Technical, and Logistical Data, Unclassified Data, January 1969.

2. Department of the Army Technical Manual, TM 5-301, Staff Tables of Engineer Functional Components System, November 1957.

3. Department of the Army Technical Manual, TM 5-302, Construction in the Theater of Operations.

4. Department of the Army Technical Manual, TM 5-303, Bills of Materials and Equipment of the Engineer Functional Components System, September 1969.

5. Department of the Army, Table of Organization and Equipment No. 5-35G, Engineer Combat Battalion, Army or Corps, October 1966.

6. Department of the Army, Table of Organization and Equipment No. 5-36G, Headquarters and Headquarters Company Engineer Combat Battalion, Army or Corps, October 1966.

7. Department of the Army, Table of Organization and Equipment No. 5-37G, Engineer Combat Company, Army or Corps, October 1966.

8. Department of the Army, Table of Organization and Equipment No. 5-58G, Engineer Light Equipment Company, January 1967.

9. Department of the Army, Table of Organization and Equipment No. 5-114G, Engineer Construction Support Company, March 1968.

10. Department of the Army, Table of Organization and Equipment No. 5-115G, Engineer Construction Battalion, June 1967.

11. Department of the Army, Table of Organization and Equipment No. 5-116G, Headquarters and Headquarters Company Engineer Construction Battalion, June 1967.

12. Department of the Army, Table of Organization and Equipment No. 5-117G, Engineer Equipment and Maintenance Company Engineer Construction Battalion, June 1967.

13. Department of the Army, Table of Organization and Equipment No. 5-118G, Engineer Construction Company Engineer Construction Battalion, June 1967.

14. Department of the Army, Table of Organization and Equipment No. 5-124G, Engineer Dump Truck Company, October 1966.

15. Department of the Army, Table of Organization and Equipment No. 5-129G, Engineer Company, Port Construction, February 1968.

16. Department of the Army, Table of Organization and Equipment No. 5-177E, Engineer Pipeline Construction Support Company, November 1966.

17. Department of the Army Regulation AR 310-32, Organization and Equipment Authorization Tables, Personnel, May 1968.

18. Gomory, R. E., "Outline of an Algorithm for Integer Solutions to Linear Programs," Bulletin of the American Mathematical Society, 64, 1958, pp. 275-278.

19. International Business Machine Application Program, "Mathematical Programming System /360 (360A-CO-14X) Linear and Separable Programming - User's Manual," H20-0476-1, 1968.

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13. ABSTRACT

Current force planning methodology for determining the proper level, mix, and balance of U.S. Army Engineer Forces required to support theater level military operations is examined and a linear programming model is described for use in the planning process. The structure of the linear programming model and feasible ways to derive required parameter values are explained in detail. A test problem and results obtained using the linear programming model are presented to amplify the explanations and to provide a basis for further evaluation and analysis. Alternate model formulations for solving minimum force, minimum cost, or maximum productivity theater force objectives, and extensions for applications of the model in force development and analysis activities are described.

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A linear programming model for use in engineering force requirements planning.